Degradation of $\beta$-Ga$_2$O$_3$ Schottky barrier diode under swift heavy ion irradiation

Wen-Si Ai(艾文思)$^{1,2}$, Jie Liu(刘杰)$^{1,2}$, Qian Feng(冯倩)$^{3,4}$, Peng-Fei Zhai(翟鹏飞)$^{1,2}$, Pei-Fei Hu(胡培培)$^{1,2}$, Jian Zeng(曾健)$^{1,2}$, Sheng-Xia Zhang(张胜霞)$^{1,2}$, Zong-Zhen Li(李宗臻)$^{1,2}$, Li Liu(刘丽)$^{1,2}$, Xiao-Yu Yan(闫晓宇)$^{1,2}$, and You-Mei Sun(孙友梅)$^{1,2}$

$^1$Institute of Modern Physics, Chinese Academy of Sciences (CAS), Lanzhou 730000, China
$^2$School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
$^3$State Key Discipline Laboratory of Wide Band Gap Semiconductor Technology, School of Microelectronics, Xi’an Jiaotong University, Xi’an 710071, China
(Received 8 February 2021; revised manuscript received 18 March 2021; accepted manuscript online 23 March 2021)

The electrical characteristics and microstructures of $\beta$-Ga$_2$O$_3$ Schottky barrier diode (SBD) devices irradiated with swift heavy ions (2096 MeV Ta ions) have been studied. It was found that $\beta$-Ga$_2$O$_3$ SBD devices showed the reliability degradation after irradiation, including turn-on voltage $V_{on}$, on-resistance $R_{on}$, ideality factor $n$, and the reverse leakage current density $J_r$. In addition, the carrier concentration of the drift layer was decreased significantly and the calculated carrier removal rates were $5 \times 10^6$–$1 \times 10^7$ cm$^{-2}$. Latent tracks induced by swift heavy ions were observed visually in the whole $\beta$-Ga$_2$O$_3$ matrix. Furthermore, crystal structure of tracks was amorphized completely. The latent tracks induced by Ta ions bombardments were found to be the reason for the decrease in carrier mobility and carrier concentration. Eventually, these defects caused the degradation of electrical characteristics of the devices. In terms of the carrier removal rates, the $\beta$-Ga$_2$O$_3$ SBD devices were more sensitive to swift heavy ions irradiation than SiC and GaN devices.

Keywords: $\beta$-Ga$_2$O$_3$ Schottky barrier diode, swift heavy ions, reliability degradation, amorphous latent track

PACS: 61.80.Jh, 61.82.Fk, 42.88.+h

DOI: 10.1088/1674-1056/abf107

1. Introduction

Monoclinic Ga$_2$O$_3$ ($\beta$-Ga$_2$O$_3$) is a traditional transparent conductive oxide material and $\beta$-Ga$_2$O$_3$ based photodetectors are attracting interest as truly solar-blind deep ultraviolet photodetectors, since they exhibit cut-off wavelengths below 280 nm.$^{[1,2]}$ This makes $\beta$-Ga$_2$O$_3$ attractive in the fields of new generation photoconductors, such as deep ultraviolet photodetectors, light-emitting diodes, and lasers. The research on $\beta$-Ga$_2$O$_3$ has been extremely hot in the past decade because of its new application in power electronic devices. $\beta$-Ga$_2$O$_3$ has not only excellent optical properties, but also a large bandgap of 4.7 eV–4.9 eV and a high critical electric field strength of 8 MV/cm.$^{[3]}$ The large bandgap and the high critical electric field strength enable $\beta$-Ga$_2$O$_3$ based devices to operate at high temperature and high power. Furthermore, $\beta$-Ga$_2$O$_3$ can be prepared by melting method, which is the same as Si and sapphire substrate. Compared with SiC and GaN, the cost advantage of $\beta$-Ga$_2$O$_3$ further promotes its application in the field of high-power electronic devices.$^{[4]}$

The $\beta$-Ga$_2$O$_3$ devices will face huge challenges used in aerospace systems despite their excellent properties. The radiation environment in outer space comprises high-energy protons, electrons, neutrons, and heavy ions.$^{[5]}$ Then, the different types of damages can be formed in the devices after different particle irradiations. For electrons, protons, and $\gamma$-rays irradiations, simple point defects are generally introduced in the wide band gap semiconductors.$^{[6,7]}$ Heavy ions and fast neutrons mainly introduce point defects or cascade displacement damages by elastic collision with target atoms.$^{[8]}$ $\beta$-Ga$_2$O$_3$ is generally considered to be radiation hardness to displacement damage due to the high bond energy and large band gap.$^{[9]}$ According to the literature, the 4H-SiC single crystal was amorphous at fluence of 0.4 dpa (displacements per atom) for 4 MeV Xe ions irradiation.$^{[10]}$ but the saturate disorder state of $\beta$-Ga$_2$O$_3$ single crystal can be reached at a higher fluence of 0.6 dpa for 700 keV Sn ions irradiation.$^{[11]}$ Moreover, the irradiation response of carrier concentration in $\beta$-Ga$_2$O$_3$ Schottky barrier diode (SBD) is similar to that of GaN devices after irradiated by electrons and protons.$^{[12]}$

Different from the above traditional particles that mainly introduce damages by interaction with the target atoms, the swift heavy ions (SHIs, > 1 MeV/u), one of the cosmic rays, mainly transfer energy to the target electrons through huge electronic energy deposition and target electrons further transfer the energy to the atoms through electron–phonon coupling.$^{[13,14]}$ When the electronic energy loss ($\Delta E$) is large
enough, a single swift heavy ion can cause local melting of material and introduce amorphous or recrystallized damage region during quenching. This damage region of nanometer in size is called latent track. In our previous study, it was found that amorphous latent tracks could be introduced in $\beta$-Ga$_2$O$_3$ single crystal when $S_e$ exceeded 17 keV/\text{nm}. However, the effect of latent tracks on the electrical characteristics of $\beta$-Ga$_2$O$_3$ devices is still not studied yet. Therefore, 2096 MeV Ta ions were used to irradiate $\beta$-Ga$_2$O$_3$ SBD devices in this work and the role of latent tracks on the reliability degradation of devices was analyzed in detail.

2. Experimental details

The vertical $\beta$-Ga$_2$O$_3$ SBD devices were used in this work. The $N^-$ $\beta$-Ga$_2$O$_3$ (001) drift layer (Sn: $\sim 1.8 \times 10^{16}$ cm$^{-3}$) of thickness 8 mm was deposited by hydride vapor phase epitaxy on 1.5 mm bulk $N^+$ substrate (Sn: $\sim 3 \times 10^{18}$ cm$^{-3}$). The metal stack of Ti/Au was deposited on the whole back of the $N^+$ substrate by E-beam evaporation and followed by the rapid thermal annealing at 500 $^\circ$C for 60 s under nitrogen atmosphere to form the Ohmic contact. The front side of the $N^-$ drift layer was patterned by lift-off of E-beam deposited Schottky contacts Ni/Au (45 nm/65 nm). The diameter of the Schottky contact was about 100 mm. The structure of the schematic across section of $\beta$-Ga$_2$O$_3$ SBD is shown in Fig. 1(a). The $\beta$-Ga$_2$O$_3$ SBD devices were divided into three groups and named #1, #2, and #3, respectively.

Heavy ion irradiation experiment was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL) in the Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS). The $\beta$-Ga$_2$O$_3$ SBD devices without electrical bias were irradiated with 2096 MeV Ta ions in the vacuum chamber. The $S_e$ and nuclear energy loss ($S_n$) were calculated by SRIM 2013 code[16] and the detail distribution of $S_e$ and $S_n$ in $\beta$-Ga$_2$O$_3$ SBD was plotted in Fig. 1(b). The range of 2096 MeV Ta ions in the device is about 50 mm, reaching deep inside the substrate far away from the metal–semiconductor (M–S) interface. Due to the limited number of samples, cumulative irradiation was adopted in this work. The devices were irradiated for the first time with the fluence of $5 \times 10^3$–$5 \times 10^8$ ions/cm$^2$, respectively. After irradiation, the irradiated samples were removed from the vacuum chamber for electrical properties measurement. Then they were continued to be irradiated until the fluence up to $1 \times 10^9$–$1 \times 10^{10}$ ions/cm$^2$, respectively. The specific irradiation parameters are listed in Table 1.

Current density–voltage ($J$–$V$) and high frequency (1 MHz) capacitance–voltage ($C$–$V$) characteristics were measured by a Keithley 4200 semiconductor parameter analyzer at room temperature. For each fluence, ten Schottky electrodes at least with almost identical electrical characteristics were analyzed. The normal behaviors of $J$–$V$ and $C$–$V$ are shown in the next section. The microstructure of $\beta$-Ga$_2$O$_3$ SBD after irradiation was characterized by bright-field TEM using a Tecnai G2 F20 S-TWIN TEM (FEI, USA) at the accelerating voltage of 200 kV.

Table 1. The irradiation fluence of the three groups of $\beta$-Ga$_2$O$_3$ SBD in the first irradiation experiment and the total fluence after the second cumulative irradiation experiment.

| Irradiation batches | #1 | #2 | #3 |
|---------------------|----|----|----|
| $1^{st}$ | $5 \times 10^7$ ions/cm$^2$ | $1 \times 10^8$ ions/cm$^2$ | $5 \times 10^8$ ions/cm$^2$ |
| $2^{nd}$ | $1 \times 10^9$ ions/cm$^2$ | $5 \times 10^9$ ions/cm$^2$ | $1 \times 10^{10}$ ions/cm$^2$ |

3. Results and discussion

Figure 2(a) shows the forward $J$–$V$ characteristics and the differential on-resistance $R_{on}$ as a function of the voltage for $\beta$-Ga$_2$O$_3$ SBD devices with different ion fluences. The results show that the forward current density decreases gradually with the increasing influence. At the forward bias of 2 V,
the maximum current density decreases from 327 A/cm² to 83 A/cm² and the \( R_{\text{on}} \) increases from 3.8 mΩ·cm² to 13.7 mΩ·cm² at the fluence of \( 1 \times 10^9 \) ions/cm². When the ion fluence increases to \( 5 \times 10^9 \) and \( 1 \times 10^{10} \) ions/cm², the \( \beta\text{-Ga}_2\text{O}_3 \) SBD devices do not exhibit forward guide characteristics and the \( R_{\text{on}} \) values reach to the order of MΩ·cm² (see Table 2). The reverse \( J-V \) characteristic also indicates the increase of the reverse leakage current density as shown in Fig. 2(b). It suggests that Ta ions irradiation can significantly affect the \( J-V \) characteristics of the \( \beta\text{-Ga}_2\text{O}_3 \) SBD devices and degrade the performance.

According to the thermionic emission theory, the relationship between the voltage and the current density can be described as

\[
J = J_a \exp \left( \frac{qV}{n(kT)} \right), \tag{1}
\]

\[
J_a = A^*T^2 \exp \left( -\frac{\Phi_B}{kT} \right), \tag{2}
\]

where \( J_a \) is the saturation current density, \( n \) is the ideality factor, \( k \) is Boltzmann’s constant, \( T \) is the absolute temperature, \( A^* \) is the effective Richardson constant \((41.1 \text{A/cm}^2 \cdot \text{K}^2)\), and \( \Phi_B \) is the Schottky barrier height. The parameters \( n \) and \( \Phi_B \) can be estimated by fitting the linear region of the \( J-V \) curve and the detail electrical parameters of \( \beta\text{-Ga}_2\text{O}_3 \) SBD devices before and after irradiation are summarized in Table 2. In order to compare the variation of electrical parameters more intuitively, the increment of each parameter (the parameter value after irradiation minus the parameter value before irradiation) is shown in Fig. 3. Since the \( \beta\text{-Ga}_2\text{O}_3 \) SBD devices do not exhibit forward guide characteristics when the fluence is up to \( 5 \times 10^9 \) and \( 1 \times 10^{10} \) ions/cm², the variations of \( V_{\text{on}} \), \( n \), and \( \Phi_B \) in Fig. 3(a) only cover in the fluence range from \( 5 \times 10^7 \) ions/cm² to \( 1 \times 10^9 \) ions/cm².

### Table 2. Comparison of experimentally calculated values of \( \beta\text{-Ga}_2\text{O}_3 \) SBD devices before and after 2096 MeV Ta ions irradiation.

| Parameters                  | Pre-irradiation | \( 5 \times 10^7 \) ions/cm² | \( 1 \times 10^8 \) ions/cm² | \( 1 \times 10^9 \) ions/cm² | \( 5 \times 10^9 \) ions/cm² | \( 1 \times 10^{10} \) ions/cm² |
|-----------------------------|-----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| \( V_{\text{on}} \) (V)    | 0.75            | 0.75                          | 0.75                          | 0.78                          | 0.76                          | 0.78                          |
| \( R_{\text{on}} \) at 2 V (mΩ·cm²) | 3.83            | 3.88                          | 3.82                          | 4.18                          | 6.16                          | 13.71                         |
| \( \Phi_B \) (eV)          | 1.01            | 1.02                          | 1.02                          | 1.04                          | 1.05                          | 1.05                          |
| \( n \)                    | 1.13            | 1.15                          | 1.12                          | 1.14                          | 1.11                          | 1.12                          |
| \( J_a \) at \(-20\text{V}\) (10\text{A/cm}²) | 2.00            | 2.00                          | 2.05                          | 3.12                          | 3.45                          | 3.75                          |
| \( N_d - N_a \) (10^{16} \text{cm}⁻³) | 1.81            | 1.79                          | 1.81                          | 1.81                          | 1.74                          | 1.15                          |
| \( R_{\text{cl}} \) (Ω·cm⁻¹) | –               | –                             | –                             | 0                             | 5 \times 10⁶                  | 1.3 \times 10⁷                |

In Fig. 3(a), both of the turn-on voltage \( V_{\text{on}} \) and ideality factor \( n \) increase with fluence increasing, while the parameter \( \Phi_B \) shows little changes. The increase of ideality factor \( n \) indicates that the current transport mechanism gradually deviates from the thermionic emission model. In general, the defects introduced by irradiation can lead to the increase of M–S interface state density and then other current transport mechanisms will participate in the process, such as tunneling.\[19,20\] The defects can also act as the capture centers of carriers, resulting in the decrease of the carrier concentration and mobility.\[21\] Hence, the on-resistance \( R_{\text{on}} \) value increases with the increase in fluence as shown in Fig. 3(b). In general, the reverse leakage current density \( J_r \) can reflect the blocking characteristic of SBD. In Fig. 3(b), the increase of \( J_r \) after irradiation indicates the degradation of blocking. This is mainly related to the reduced carrier lifetime due to the increase of deep level recombination centers in the barrier region after irradiation.\[22\]

![Fig. 3. The increments of electrical parameters (turn-on voltage \( V_{\text{on}} \), ideality factor \( n \), Schottky barrier height \( \Phi_B \), reverse leakage current density \( J_r \), on-resistance \( R_{\text{on}} \)) as a function of fluence before and after irradiation.](attachment:image1)

![Fig. 4. The \( C-V \) and \( 1/C^2-V \) characteristics (1 MHz) of the devices after 2096 MeV Ta ions irradiation.](attachment:image2)

\[
\frac{1}{C^2} = \frac{2}{q\varepsilon A^2 (N_d - N_a)} (V_{\text{bi}} - V), \tag{3}
\]

where \( q \) is the electron charge, \( A \) is the area of the Schottky diode, \( \varepsilon \) is the dielectric constant (\( \text{Ga}_2\text{O}_3 \), \( \varepsilon = 10\varepsilon_0 \)), \( V_{\text{bi}} \) is the built-in potential, and \( N_d - N_a \) stands for the carrier concentration in the drift layer. The carrier concentration can be extracted from the slope of the \( 1/C^2 \)–\( V \) curve and the results
are listed in Table 2. Only the carrier concentrations in the drift layer are calculated with the fluence range of $5 \times 10^7 - 1 \times 10^9$ ions/cm$^2$. The corresponding variation of normalized carrier concentration is summarized in Fig. 5(a).

According to Fig. 5(a), it is clear that the carrier concentration in the drift $\beta$-Ga$_2$O$_3$ layer shows little changes at the fluence of $5 \times 10^7$ ions/cm$^2$. However, the carrier concentration decreases significantly as the fluence increases from $1 \times 10^8$ ions/cm$^2$ to $1 \times 10^9$ ions/cm$^2$. At the fluence of $1 \times 10^9$ ions/cm$^2$, the normalized carrier concentration is only 30% that of the unirradiated samples. The acceptor-defects introduced by Ta ions result in the decrease of the carrier concentration, further cause the increase of the depletion width, and finally show that the capacitance in C-V measurement decreases with the increase of fluence. As the fluence increases further to $5 \times 10^9$ ions/cm$^2$ and $1 \times 10^{10}$ ions/cm$^2$, the excessively low carrier concentration is equivalent to the infinite width of the depletion layer and the Schottky barrier capacitance disappears.

According to the carrier concentration, the carrier removal rate $R_c$ is calculated and the results are plotted in Fig. 5(b). The carrier removal rate $R_c$ relates to the removal of carriers by deep traps which are induced by the radiation. It is related to the fluence $\varphi$ and the decrease value of carrier concentration $\Delta(N_d - N_a)$ through the equation:

$$R_c \varphi = \Delta(N_d - N_a).$$

The $R_c$ can provide a practical guide for estimating the degree of the degradation induced in the devices or materials for a given fluence of the common type of radiation. In this work, the calculated $R_c$ is $5 \times 10^6$ cm$^{-1}$ for $\beta$-Ga$_2$O$_3$ SBD irradiated with Ta ions to the fluence of $1 \times 10^9$ ions/cm$^2$ and it reaches saturation the value of $1.3 \times 10^7$ cm$^{-1}$ at the fluence of $5 \times 10^8$ ions/cm$^2$. In general, $R_c$ is linear increasing with the fluence at the lower fluence. However, if most of the carriers are removed at a higher fluence, the excess defects will not contribute to the carrier removal effect any more. Thus, the relationship between $R_c$ and the fluence $\varphi$ will not follow the linear relationship.[6]

The carrier removal rates of $\beta$-Ga$_2$O$_3$ based devices irradiated by different types of ions are summarized in Fig. 6(a) (red symbols). Note that the carrier removal rate is 406–728 cm$^{-1}$ for $\alpha$ particles irradiation,[27] 300 cm$^{-1}$ for 10 MeV protons,[12] 4.9 cm$^{-1}$ for 1.5 MeV electrons,[26] and 19–28 cm$^{-1}$ for 1.25 MeV neutrons[25] in $\beta$-Ga$_2$O$_3$ SBD devices or rectifiers. However, the carrier removal rates for SHIs in this work are much higher. This indicates that the energetic Ta ions exhibit the highest carrier removal rates among these ions irradiation, and it can be explained by the damage type caused by SHIs.

The cross-sectional TEM of the $\beta$-Ga$_2$O$_3$ SBD irradiated by 2096 MeV Ta ions to a fluence of $1 \times 10^{10}$ ions/cm$^2$. The irradiation direction is indicated by white arrows and the latent tracks parallel to each other are marked by red arrows.
Figure 6(a) also summarizes the carrier removal rates of GaN or SiC based devices including SBD devices and high electron mobility transistors (HEMTs).[16,22,28–32] It can be extracted from Fig. 6(a) that under the irradiation environment of high-energy electrons, protons, and heavy ions, which mainly introduce displacement damages by elastic collision with the target atoms, the $R_e$ values of $\beta$-Ga$_2$O$_3$ SBD or rectifier are similar to those of GaN or SiC based devices, indicating the excellent radiation hardness of $\beta$-Ga$_2$O$_3$ devices. This can be attributed to the higher formation energy of vacancy defects in $\beta$-Ga$_2$O$_3$.\footnote{13–25} However, the degradation of $\beta$-Ga$_2$O$_3$ SBD is more serious than that of SiC or GaN devices under the SHIs irradiation as the shadow shown in Fig. 6(a). In addition, $\beta$-Ga$_2$O$_3$ SBD devices in our work are completely damaged under 2096 MeV Ta ions irradiation with fluence of $5 \times 10^9$ ions/cm$^2$. However, the GaN HEMTs reported by Hu et al.\cite{36} were still functional after swift heavy Bi ions irradiation with energy of 1500 MeV to the fluence of $1.7 \times 10^{11}$ ions/cm$^2$.

Based on the thermal spike model,\footnote{37} the latent track is formed through the material melting and quenching rapidly along the path of SHIs. Hence, thermodynamic properties and recrystallization ability of the target material are the main factors affecting the latent track formation.\footnote{38} The poor thermal conductivity and recrystallization ability of $\beta$-Ga$_2$O$_3$ make the $S_e$ threshold of latent track formation in $\beta$-Ga$_2$O$_3$ (17 keV/nm) lower than that of SiC (> 34 keV/nm) and GaN (23–28 keV/nm).\footnote{15} Therefore, the damage introduced by SHIs in the whole $\beta$-Ga$_2$O$_3$ matrix has a greater impact on the degradation of $\beta$-Ga$_2$O$_3$ SBD devices than the damage in M–S interface.

4. Conclusion

We studied the degradation and the structure damages of $\beta$-Ga$_2$O$_3$ SBD devices after 2096 MeV Ta ions irradiation with the fluence range from $5 \times 10^7$ ions/cm$^2$ to $1 \times 10^{10}$ ions/cm$^2$. Both the conducting and blocking characteristics were sensitive to the ion irradiation. A strong reduction of the carrier was observed and the carrier removal rates were $5 \times 10^6$–1.3 $\times 10^7$ cm$^{-1}$. Furthermore, the amorphous latent tracks along the ions trajectories cross the whole area of the drift layer were responsible for the decrease in carrier concentration and mobility, and resulted in the deterioration of the $\beta$-Ga$_2$O$_3$ SBD devices. In addition, the damage introduced by SHIs in the whole $\beta$-Ga$_2$O$_3$ matrix had a greater impact on the degradation of $\beta$-Ga$_2$O$_3$ SBD devices than the damage in M–S interface. The serious degradation of $\beta$-Ga$_2$O$_3$ SBD indicates the worse radiation hardness of $\beta$-Ga$_2$O$_3$ based device compared with SiC and GaN devices.

References

[1] Pearton S, Yang J, Carey P, Ren F, Kim J, Tadjer M and Mastro M 2018 J. Phys.: Conf. Ser. 129 012055

[2] Ueda N, Hosono H, Waseda R and Kawasaki H 1997 Appl. Phys. Lett. 71 933

[3] Zeng K, Vaidya A and Singisetti U 2018 IEEE Electron Device Lett. 39 1385

[4] Reese S B, Remo T, Green J and Zakutayev A 2019 J. Appl. Phys. 126 035704

[5] Claey S and Simoen E 2002 Radiation Effects in Advanced Semiconductor Materials and Devices (New York: Springer Berlin Heidelberg)

[6] Pearton S J, Ren F, Patrick E, Law M E and Polyakov A Y 2016 ECS J. Solid State Sci. Technol. 5 Q35–60

[7] Pearton S J, Deist R, Ren F, Liu L, Polyakov A Y and Kim J 2013 J. Vac. Sci. Technol. A 31 50801

[8] Janousek B K, Yamada W E, Krantz R J and Bloss W L 1988 J. Appl. Phys. 63 1678

[9] Yang G, Jiang S P, Ren F, Pearton S and Kim J 2017 ACS Appl. Mater. Interfaces 9 40471

[10] Kerbiriou X, Costantini J M, Sauzay M, Sorieul S, Thomé L, Jagielski J and Grob J J 2009 J. Appl. Phys. 105 75315

[11] Wendler E, Treiber E, Baldauf J, Wolf S and Ronning C 2016 Nucl. Instrum. Methods B 379 85

[12] Yang J, Chen Z, Ren F, Pearton S, Yang G, Kim J, Lee J, Flitsiany E, Chernyak L and Kuramata A 2018 J. Vac. Sci. Technol. B 36 11206

[13] Komarov F F 2003 Nucl. Instrum. Methods B 184 1253

[14] Aumayr F, Facsko S, El-Said A S, Trautmann C and Schleberger M 2011 J. Phys. Condens. Matter 23 393001

[15] Ai W, Xu L, Nan S, Zhai P, Li W, Li Z, Hu P, Zeng J, Zhang S, Liu L, Sun Y and Liu J 2019 Jpn. J. Appl. Phys. 58 120914

[16] Ziegler J F and Biersack J P 2013 http://www.srim.org/

[17] Wang L, Nathan M I, Lim T, Khan M A and Chen Q 1996 Appl. Phys. Lett. 68 1267

[18] Shur M 1990 Physics of Semiconductor Devices (New Jersey: Prentice Hall, Inc.)

[19] Kumar A, Singh R, Kumar P, Singh U, Kandamasi A, Karasev P, Titov A and Kanjilal D 2018 J. Phys. Appl. Phys. 123 165139

[20] Kumar S, Katharria Y, Batra Y and Kanjilal D 2007 J. Phys. D: Appl. Phys. 40 6892

[21] Manikanthabahu N, Tak B, Kunche P, Sarkar S, Kandamasi A, Kanjilal D, Barman R S, Singh R and Panigrahi B 2020 Appl. Phys. Lett. 117 142015

[22] Yang Z, Mu Y, Gong M, Li Y, Huang M, Gao B and Zhao X 2017 Nucl. Instrum. Methods B 401 51

[23] Neamen D A 2011 Semiconductor Physics and Devices: Basic Principles (Boston: McGraw-Hill Co.)

[24] Jun B and Subramanian S 2003 IEEE Trans. Nucl. Sci. 49 3222

[25] Polyakov Y, Y Smirnov N B, Schchemerov I V, Vasilev A A, Yakimov E B, Chernykh Y V, Kovalchuk A I, Logov P B, Pavlov Y S, Kukharukh O F, Suvorov A A, Garaun W S, Lee I H, Xian M, Ren F and Han M 2010 J. Phys. D: Appl. Phys. 43 125201

[26] Yang J, Ren F, Pearton S, Yang G, Kim J and Kuramata A 2017 J. Vac. Sci. Technol. A 35 31208

[27] Yang J, Fares C, Guan Y, Ren F, Pearton S, Bae J, Kim J and Kuramata A 2018 J. Vac. Sci. Technol. B 36 31205

[28] Kumar V, Maan A and Akhtar J 2018 Phys. Status Solidi A 215 1700555

[29] Ma G, Zhang Y, Li H, Liu C, Qi C, Wei Y, Wang T, Dong S and Huo M 2019 IEEE 26th International Symposium on Physical and Failure Analysis of Integrated Circuits (IPFA) Hangzhou, 2019 pp. 1–5

[30] Mikelsen M, Grossner U, Bleka J H, Monakhov E V, Svensson B G, Yakimova R, Henry A, Junzén E and Lebedev A A 2008 Mater. Sci. Forum 600–603 425

[31] Omototo E, Meyer W E, Aurel F D, Diñe M and Nguepepo P N M 2016 Physica B 480 196

[32] Yang J, Li H, Dong S and Li X 2019 IEEE Trans. Nucl. Sci. 66 2042

[33] Blanco M, Sahariah M, Jiang H, Costales A and Pandey R 2005 Phys. Rev. B 72 184103

[34] Miceli G and Pasquarello A 2015 Microelectron. Eng. 147 51

[35] Gao F and Weber W J 2002 Nucl. Instrum. Methods B 191 504

[36] Hu P P, Liu J, Zhang S X, Mazz K, Zeng J, Zhai P F, Xu L L, Cao Y R, Duan J L, Li Z Z, Sun Y M and Ma X H 2018 Nucl. Instrum. Methods B 430 59

[37] Toulmonde M, Bouffard S and Studer F 1994 Nucl. Instrum. Methods B 91 108

[38] Ryzhunov R A, Medvedev N, O’Connell J H, Janse van Vuuren A, Skuratov V A and Volkov A E 2019 J. Appl. Phys. 125 3937