10 MeV proton damage in β–Ga_2O_3 Schottky rectifiers

Jiancheng Yang, Zhiting Chen, Fan Ren, S. J. Pearton, Gwangseok Yang, Jihyun Kim, Jonathan Lee, Elena Flitsiyan, Leonid Chernyak, and Akito Kuramata

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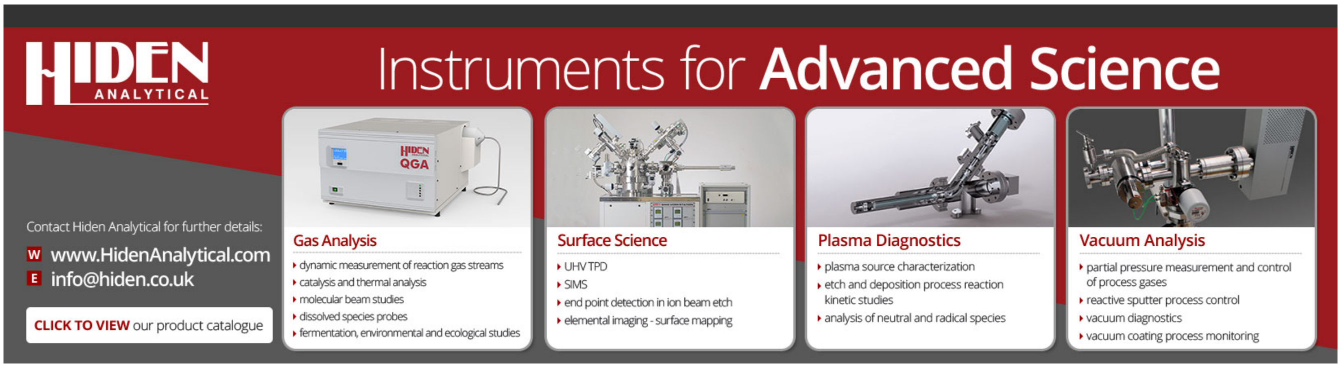

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10 MeV proton damage in β-Ga_2O_3 Schottky rectifiers

Jiancheng Yang, Zhiting Chen, and Fan Ren
Department of Chemical Engineering, University of Florida, Gainesville, Florida 32611

S. J. Pearton[a)]
Department of Materials Science and Engineering, University of Florida, Gainesville, Florida 32611

Gwangseok Yang and Jihyun Kim
Department of Chemical and Biological Engineering, Korea University, Seoul 136-713, South Korea

Jonathan Lee, Elena Flitsiyan, and Leonid Chernyak
Department of Physics, University of Central Florida, Orlando, Florida 32816

Akito Kuramata
Tamura Corporation and Novel Crystal Technology, Inc., Sayama, Saitama 350-1328, Japan

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The electrical performance of vertical geometry Ga_2O_3 rectifiers was measured before and after 10 MeV proton irradiation at a fixed fluence of $10^{14}\,cm^{-2}$, as well as subsequent annealing up to 450 °C. Point defects introduced by the proton damage create trap states that reduce the carrier concentration in the Ga_2O_3, with a carrier removal rate of $235.7\,cm^{-1}$ for protons of this energy. The carrier removal rates under these conditions are comparable to GaN-based films and heterostructures. Even annealing at 300 °C produces a recovery of approximately half of the carriers in the Ga_2O_3, while annealing at 450 °C almost restores the reverse breakdown voltage. The on/off ratio of the rectifiers was severely degraded by proton damage and this was only partially recovered by 450 °C annealing. The minority carrier diffusion length decreased from ~340 nm in the starting material to ~315 nm after the proton irradiation. The reverse recovery characteristics showed little change with values in the range 20–30 ns before and after proton irradiation. *Published by the AVS.* https://doi.org/10.1116/1.5013155

I. INTRODUCTION

β-Ga_2O_3 is attracting interest for power electronics and solar blind photodetectors because of its large bandgap (~4.9 eV) and critical electric field (E_C) strength of $8\,MV\,cm^{-1}$ and the ready availability of high quality, large area wafers.[1–18] There is always interest in the ability of wide bandgap semiconductors to withstand high radiation fluences of the type encountered in satellite or other space-borne applications.[19] Given its high bond strength and expected high vacancy formation energy, β-Ga_2O_3 is likely to be very radiation hard based on the reduced density of atomic displacements expected for a given energy of nonionizing radiation exposure. In general, the bond energies scale with bandgap, meaning, for example, that a material like GaN with a bandgap of 3.4 eV is likely to be more radiation hard than GaAs with a bandgap of 1.43 eV.[20–30] However, it has been pointed out by Weaver *et al.*[20] that while fewer defects are created in GaN than in GaAs because of the larger values of E_d, the difference (36%) is insufficient to explain the order-of-magnitude (1000%) difference in radiation tolerance.[31–36] They suggested that creation of Ga vacancies, which are triple acceptors, causes the number of acceptors to significantly increase and (N_d–N_a) to decrease.[20] It is not yet clear whether a similar explanation can be applied to other wide bandgap materials, or this is specific to the case of GaN. Korhonen *et al.*[37] investigated the electrical compensation in n-type Ga_2O_3 by Ga vacancies in Ga_2O_3 thin films using positron annihilation spectroscopy. They estimated a V_{Ga} concentration of at least $5 \times 10^{18}\,cm^{-3}$ in their undoped and Si-doped samples.[37] Since theoretical calculations predicts that these V_{Ga} should be in a negative charge state for n-type samples,[3,5] they will compensate the *n*-type doping. Kananen *et al.*[38] used EPR to demonstrate the presence of both doubly ionized ($V_{Ga}{}^{2-}$) and singly ionized ($V_{Ga}{}^{-}$) acceptors at room temperature in Czochralski Ga_2O_3.

There are three principal sources of space radiation, namely, from cosmic rays, trapped radiation in the Earth's radiation belts, and finally, solar particle events.[19] The cosmic rays consist predominantly of protons, the radiation belts contain energetic protons and electrons, while solar particle events are mostly lower energy protons and electrons, in which the typical integral proton fluxes at 10 MeV are of order $10^{14}\,cm^{-2}$.[19] Thus, it is important to understand the effect of energetic proton irradiation on Ga_2O_3.

There are now some initial reports of the effect of proton, electron, gamma ray and neutron irradiation of n-type β-Ga_2O_3 rectifiers and UV photodetectors under conditions relevant to low earth orbit of satellites containing these types of devices.[23–27] The carrier removal rates for proton, electron and neutron irradiation are found to be comparable to those in GaN of similar doping levels for the same types of fluences.[23–27] The main defect created in Ga_2O_3 by proton irradiation has been identified as a Ga vacancy with two hydrogens attached.[39] Neutron irradiation produces a dominant state with an ionization level near $E_C - 1.88\,eV$.[26]

In this paper, we discuss the effect of 10 MeV proton irradiation on vertical β-Ga_2O_3 Schottky rectifiers, which provide a convenient platform for monitoring changes in the properties of Ga_2O_3 subject to radiation fluences. The carrier removal rate is found to be $\sim 236\,cm^{-1}$ for this proton

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[a)] Electronic mail: spear@mse.ufl.edu

energy. The results are contrasted with the behavior of GaN subjected to similar exposures.

II. EXPERIMENT

The starting samples were bulk β-phase Ga_2O_3 single crystal wafers ($\sim$650 μm thick) with (001) surface orientation grown by the edge-defined film-fed growth method.[1] Hall measurements showed the Sn-doped samples had carrier concentration of 2.2×10^{18} cm^{-3}. Epitaxial layers (initially $\sim$20 μm thick) of lightly Si-doped n-type Ga_2O_3 ($\sim 3 \times 10^{16}$ cm^{-3}) were grown on these substrates by hydride vapor phase epitaxy. After growth, the episurface was subjected to chemical mechanical polishing to planarize the surface, with a final thickness of $\sim$10 μm.

Diodes were fabricated by depositing a full area back Ohmic contacts of Ti/Au (20 nm/80 nm) by e-beam evaporation. The front sides were patterned by lift-off of electron-beam deposited Schottky contacts Ni/Au (20 nm/80 nm) with 210 μm. Figure 1 shows a schematic of the rectifier layer structure. Current–voltage (I-V) characteristics were recorded at 25 °C on an Agilent 4145B parameter analyzer or a Tektronix 370A curve tracer. The 10-MeV proton beam was generated using a MC-50 Cyclotron at the Korea Institute of Radiological and Medical Science. The proton beam was injected into a low-vacuum chamber, where the β-Ga_2O_3-based devices were loaded, facing the proton beam. The average beam-current, measured by Faraday-cup, was 100 nA during the proton irradiation process. Proton fluence was fixed at 10^{14} cm^{-2}. The projected range of the 10-MeV proton beam was calculated using the stopping and range of ions in matter program and is 330 μm, which is well into the substrate. Minority carrier diffusion length, L, was determined using the electron beam-induced current (EBIC) method on these same Schottky contacts. The EBIC was recorded during line-scans of 10 s duration performed with a Philips XL-30 scanning electron microscope.[40,41] Samples were annealed in flowing N_2 ambient in a surface science integration rapid thermal annealing system in the range of 300–450 °C for 30 s.

III. RESULTS AND DISCUSSION

The reverse bias I-V characteristics shown in Fig. 2 demonstrate that the proton irradiation caused a significant increase in breakdown voltage. This is a result of carrier removal in the epilayer by nonionizing energy loss that creates electron traps and acceptor states that compensate the initial donor doping. Yang *et al.*[27] reported a decrease in both channel conductivity and mobility in proton irradiated β-Ga_2O_3 nanobelt field effect transistors. The latter occurs because of the more significant Coulombic carrier scattering as charged defects are created by the proton energy loss during their stopping process. Note that postirradiation annealing produced a partial recovery of the I-V characteristics. This is consistent with the behavior reported earlier for dry etch-induced damage to the near-surface of Ga_2O_3, where annealing at 450 °C was found to essentially restore the values of barrier height and ideality factor of plasma damaged diodes.[28]

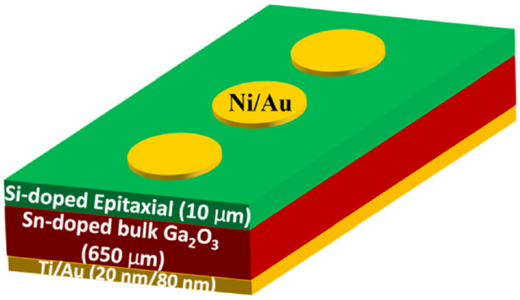

FIG. 1. (Color online) Schematic of vertical Ni/Au Schottky diode on Ga_2O_3 epilayer doped at 3.1×10^{16} cm^{-3} on a conducting β-Ga_2O_3 substrate doped at 2.2×10^{18} cm^{-3}.

The recovery in electrical properties is also reflected in the $1/C^2$-V plots for the rectifiers after proton irradiation and subsequent annealing shown in Fig. 3. The calculated carrier removal rate was 235.7 cm^{-1} for the 10 MeV protons. The initial carrier density of 3.1×10^{16} cm^{-3} was reduced to 8.03×10^{15} cm^{-3} after proton irradiation and annealing at 300 °C restored this approximately half-way, to 1.87×10^{16} cm^{-3}. This compares with a carrier removal rate of $\sim$4.9 cm^{-1} for 1.5 MeV electron irradiation of the same type of rectifiers.[25] Thus, the protons are roughly 50 times more damaging than the electrons.

Figure 4 shows the rectifier on/off ratio when switching from +1 V forward bias to the reverse voltages shown on the x-axis. The unirradiated rectifiers showed on/off ratios of $>10^5$ across the entire voltage range investigated. This is severely degraded by proton irradiation, to values in the range 10^2–10^3. This is due to the reduction of forward current as the carrier density is reduced the by the proton damage-induced trap introduction. Annealing at 300 °C did not have a significant recovery effect, while annealing at 450 °C restored the on/off ratios to $\sim 10^4$. These results show how the operating characteristics of the rectifiers are degraded by exposure to high energy proton fluences.

Figure 5 shows a compilation of reported carrier removal rates for GaN-based heterostructures (AlGaN/GaN and InAlN/GaN high electron mobility transistor structures)[21,22] along with single layers of n-or p-GaN as a function of radiation type and energy. Note that protons exhibit the highest

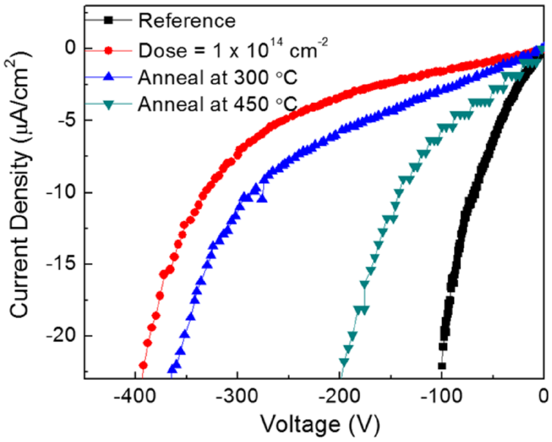

FIG. 2. (Color online) Reverse current density–voltage characteristics before and after 10 MeV proton irradiation with the fluence 10^{14} and then annealed at either 300 or 450 °C.

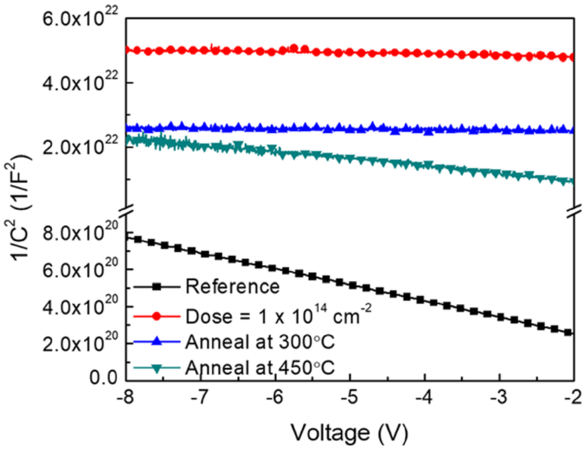

FIG. 3. (Color online) C^{-2}-V characteristics of Ga_2O_3 rectifiers before and after proton irradiation and subsequent annealing at either 300 or 450 °C.

carrier removal rates of the four types of radiation represented. We have plotted the results obtained here for proton irradiation of Ga_2O_3, as well as previously reported values for electron[25] and neutron irradiation.[26] The results for Ga_2O_3 are generally comparable to those for GaN and indicate that the former is a good candidate for space-borne applications.

The EBIC technique was used to determine minority carrier diffusion length as a function of temperature for each irradiation dose.[40,41] Figure 6 (top) shows a wire-bonded rectifier packaged for this measurement. As shown in Fig. 6 (bottom), the room temperature value of L was ~340 nm for the nonirradiated sample and decreased with increasing temperature due to increased scattering or recombination. After proton irradiation, the room temperature diffusion length was reduced to ~315 nm. The diffusion length depends exponentially on temperature through an Arrhenius factor. The values of the activation energy were 41.8 and 16.2 meV for the nonirradiated and proton irradiated samples, respectively.

We also measured the reverse recovery characteristics when switching from +1 V to a range of reverse biases and found recovery times of order 20–30 ns for both control and proton irradiated rectifiers, as shown in Fig. 7. We have reported previously in electron irradiated rectifiers that the reverse recovery shows little change with radiation dose,[25] since the minority carrier lifetime (which controls the carrier storage time in the intrinsic layer) is already small in Ga_2O_3.

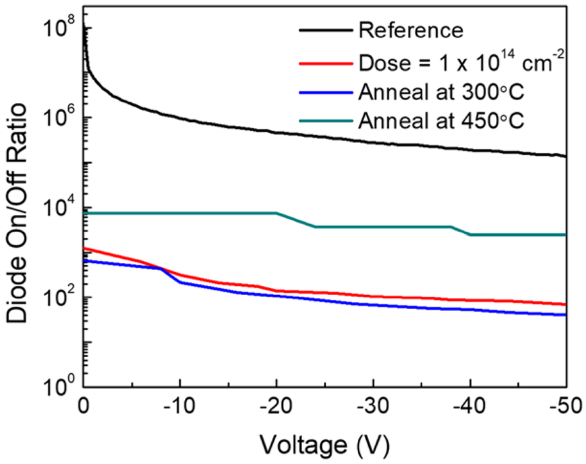

FIG. 4. (Color online) On/off ratio as a function of reverse bias voltage for rectifiers before and after proton irradiation and subsequent annealing at either 300 or 450 °C.

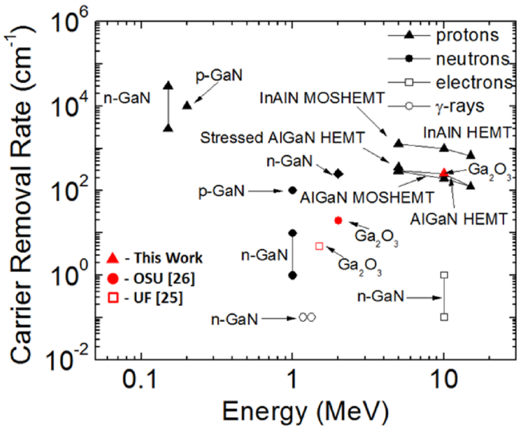

FIG. 5. (Color online) Carrier removal rate for radiation damage of Ga_2O_3 measured in this work and also reported previously, as a function of radiation type and energy. Similar data for various types of GaN-based high electron mobility transistors and thin films are shown for comparison.

IV. SUMMARY AND CONCLUSIONS

Ga_2O_3 rectifiers were irradiated with 10 MeV protons to a fixed fluence of 10^{14} cm^{-2}. The carrier removal rate in the

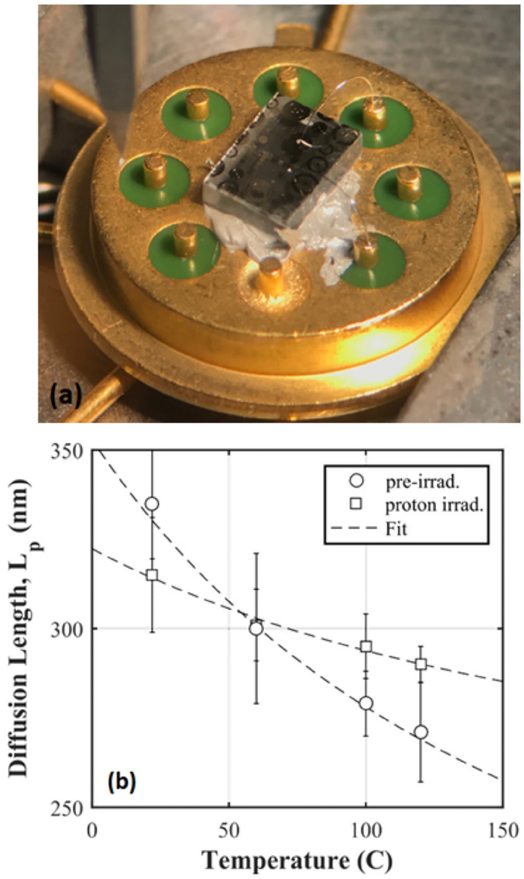

FIG. 6. (Color online) Optical image of wire-bonded Ga_2O_3 rectifier (top) and measured diffusion length as a function of temperature for control and proton irradiated rectifiers (bottom).

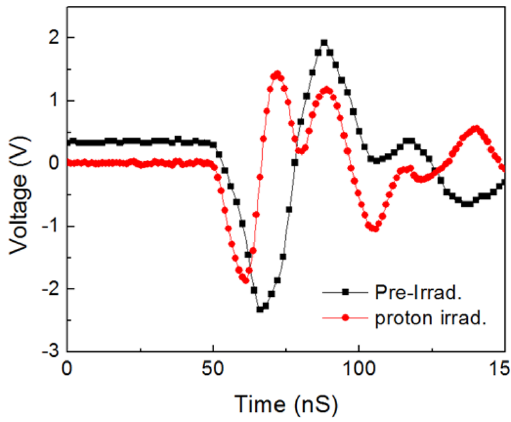

FIG. 7. (Color online) Reverse recovery characteristics of rectifiers before and after proton irradiation.

drift region of the rectifiers was 235.7 cm^{-1} under these conditions. The reverse breakdown voltage increases in response to a reduction in channel carrier density and the on/off ratio and minority carrier diffusion length are also degraded. Recovery of the damage begins at 300 °C, while annealing at 450 °C brings significant recovery of carrier density. The carrier removal rates are Ga_2O_3 are comparable to those in GaN under similar conditions.

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[1] A. Kuramata, K. Koshi, S. Watanabe, Yu Yamaoka, T. Masui, and S. Yamakoshi, Jpn. J. Appl. Phys., Part 1 **55**, 1202A2 (2016).
[2] M. Baldini, Z. Galazka, and G. Wagner, "Recent progress in the growth of β-Ga_2O_3 for power electronics applications," Mater. Sci. Semicond. Process. (published online).
[3] S. I. Stepanov, V. I. Nikolaev, V. E. Bougrov, and A. E. Romanov, Rev. Adv. Mater. Sci. **44**, 63 (2016), available at http://www.ipme.ru/e-journals/RAMS/no_14416/06_14416_stepanov.pdf.
[4] M. A. Mastro, A. Kuramata, J. Calkins, J. Kim, F. Ren, and S. J. Pearton, ECS J. Solid State Sci. Technol. **6**, P356 (2017).
[5] H. Von Wenckstern, Adv. Electron. Mater. **3**, 1600350 (2017).
[6] Z. Galazka *et al.*, ECS J. Solid State Sci. Technol. **6**, Q3007 (2017).
[7] M. J. Tadjer *et al.*, Phys. Status Solidi A **213**, 893 (2016).
[8] M. Kim, J.-H. Seo, U. Singisetti, and Z. Ma, J. Mater. Chem. C **5**, 8338 (2017).
[9] A. T. Neal, S. Mou, R. Lopez, J. V. Li, D. B. Thomson, K. D. Chabak, and G. H. Jessen, Sci. Rep. **7**, 13218 (2017).
[10] S. Rafique, L. Han, and H. Zhao, ECS Trans. **80**, 203 (2017).
[11] M. J. Tadjer *et al.*, J. Electron. Mater. **45**, 2031 (2016).
[12] S. Rafique, L. Han, M. J. Tadjer, J. A. Freitas, Jr., N. A. Mahadik, and H. Zhao, Appl. Phys. Lett. **108**, 182105 (2016).
[13] M. Higashiwaki, K. Sasaki, A. Kuramata, T. Masui, and S. Yamakoshi, Appl. Phys. Lett. **100**, 013504 (2012).
[14] M. Higashiwaki, K. Sasaki, H. Murakami, Y. Kumagai, A. Koukitu, A. Kuramata, T. Masui, and S. Yamakosh, Semicond. Sci. Technol. **31**, 034001 (2016).
[15] A. J. Green *et al.*, IEEE Electron. Device Lett. **37**, 902 (2016).
[16] M. H. Wong, K. Sasaki, A. Kuramata, S. Yamakoshi, and M. Higashiwaki, IEEE Electron. Device Lett. **37**, 212 (2016).
[17] M. J. Tadjer, N. A. Mahadik, V. D. Wheeler, E. R. Glaser, L. Ruppalt, A. D. Koehler, K. D. Hobart, C. R. Eddy, Jr., and F. J. Kub, ECS J. Solid State Sci. Technol. **5**, 468 (2016).
[18] K. D. Chabak *et al.*, Appl. Phys. Lett. **109**, 213501 (2016).
[19] E. R. Benton and E. V. Benton, Nucl. Instrum. Methods Phys. Res., B **184**, 255 (2001).
[20] B. D. Weaver, T. J. Anderson, A. D. Koehler, J. D. Greenlee, J. K. Hite, D. I. Shahin, F. J. Kub, and K. D. Hobart, ECS J. Solid State Sci. Technol. **5**, Q208 (2016).
[21] S. J. Pearton, F. Ren, E. Patrick, M. E. Law, and A. Y. Polyakov, ECS J. Solid State Sci. Technol. **5**, Q35 (2016).
[22] S. J. Pearton, R. Deist, F. Ren, L. Liu, A. Y. Polyakov, and J. Kim, J. Vac. Sci. Technol., A **31**, 050801 (2013).
[23] S. Ahn *et al.*, J. Vac. Sci. Technol., B **34**, 041213 (2016).
[24] D. Szalkai, Z. Galazka, K. Irmscher, P. Tüttő, A. Klix, and D. Gehre, IEEE Trans. Nucl. Sci. **64**, 1574 (2017).
[25] J. Yang, F. Ren, S. J. Pearton, G. Yang, J. Kim, and A. Kuramata, J. Vac. Sci. Technol., B **35**, 031208 (2017).
[26] A. A. Arehart, E. Farzana, T. E. Blue, and S. A. Ringel, paper presented at 2nd International Workshop on Ga2O3 and Related Materials, Parma, Italy, September (2017).
[27] G. Yang, S. Jang, F. Ren, S. J. Pearton, and J. Kim, ACS Appl. Mater. Interface **9**, 40471 (2017).
[28] J. Yang *et al.*, J. Vac. Sci. Technol., B **35**, 051201 (2017).
[29] K. Konishi, K. Goto, H. Murakami, Y. Kumagai, A. Kuramata, S. Yamakoshi, and M. Higashiwaki, Appl. Phys. Lett. **110**, 103506 (2017).
[30] S. Ahn, F. Ren, L. Yuan, S. J. Pearton, and A. Kuramata, ECS J. Solid State Sci. Technol. **6**, P68 (2017).
[31] T. J. Anderson, A. D. Koehler, J. D. Greenlee, B. D. Weaver, M. A. Mastro, J. K. Hite, C. R. Eddy, F. J. Kub, and K. D. Hobart, IEEE Electron Device Lett. **35**, 826 (2014).
[32] J. D. Greenlee *et al.*, Appl. Phys. Lett. **107**, 083504 (2015).
[33] J. Lee, E. Flitsiyan, L. Chernyak, J. Salzman, and B. Meyler, ECS J. Solid State Sci. Technol. **6**, S3063 (2017).
[34] T. J. Anderson, A. D. Koehler, J. A. Freitas, Jr., B. D. Weaver, J. D. Greenlee, M. J. Tadjer, E. A. Imhoff, K. D. Hobart, and F. J. Kub, ECS J. Solid State Sci. Technol. **5**, Q289 (2016).
[35] T. J. Anderson, D. J. Meyer, A. D. Koehler, J. A. Roussos, B. D. Weaver, K. D. Hobart, and F. J. Kub, ECS J. Solid State Sci. Technol. **6**, S3110 (2017).
[36] J. C. Gallagher, T. J. Anderson, A. D. Koehler, N. A. Mahadik, A. Nath, B. D. Weaver, K. D. Hobart, and F. J. Kub, ECS J. Solid State Sci. Technol. **6**, S3060 (2017).
[37] E. Korhonen, F. Tuomisto, D. Gogova, G. Wagner, M. Baldini, Z. Galazka, R. Schewski, and M. Albrecht, Appl. Phys. Lett. **106**, 242103 (2015).
[38] B. E. Kananen, L. E. Halliburton, K. T. Stevens, G. K. Foundos, K. B. Chang, and N. C. Giles, Appl. Phys. Lett. **110**, 202104 (2017).
[39] P. Weiser, M. Stavola, W. Beall Fowler, Y. Qin, and S. Pearton, "Structure and vibrational properties of OH centers in β-Ga_2O_3," Appl. Phys. Lett. (submitted).
[40] L. Chernyak, A. Osinsky, and A. Schulte, Solid-State Electron. **45**, 1687 (2001).
[41] O. Lopatiuk-Tirpak, L. Chernyak, L. J. Mandalapu, Z. Yang, J. L. Liu, K. Gartsman, Y. Feldman, and Z. Dashevsky, Appl. Phys. Lett. **89**, 142114 (2006).