Study of BGaN semiconductor for novel neutron semiconducting detector

Takayuki Nakano[1,2], Toru Aoki[2]

nakano.takayuki@shizuoka.ac.jp
[1]Dept.of Electronics and Materials Science, Shizuoka University, Hamamatsu 432-8561 Japan
[2] Research Institute of Electronics, Shizuoka University, Hamamatsu 432-8011 Japan
Keywords: BGaN, neutron detection, radiation detection semiconductor detector, group-III nitride.

ABSTRACT

BGaN semiconductor is expected as a novel neutron detection technology because of including B atom, which has large neutron capture cross section. Furthermore, BGaN has high-temperature tolerance and is expected as a radiation detector in a high-temperature conditions. In this study, the temperature tolerance of BGaN semiconductor detectors was investigated.

1 Introduction

Recently, BGaN is expected as a novel neutron detection semiconductor material because of a large neutron captured cross sectional area of boron (B) atoms and the low γ-ray detection sensitivity of BGaN [1.2]. Such a neutron detection device requires thick BGaN epitaxial growth to detect charged particles with a path length of 5 μm generated by the ^{10}B (n, α) ^{7}Li reaction. The thick BGaN epitaxial growth is known to be difficult, because the vapor phase reaction derived from B metalorganic sources. However, the use of trimethylboron (TMB) as a B metalorganic source has suppressed the vapor phase reaction and has led to the achievement of thick film epitaxial growth [3]. Furthermore, BGaN, a group-III nitride semiconductor, is a mixed alloy semiconductor of BN and GaN and is a wide bandgap semiconductor. From these futures, BGaN has high-temperature tolerance and is expected as a radiation detector in high-temperature conditions. In this study, radiation detection and electrical properties of a pin-BGaN, pin-GaN, and pn-GaN diode detector were evaluated in high-temperature conditions.

2 Experiment

The metal-organic vapor phase growth (MOVPE) method was used for GaN and BGaN epitaxial growth. The electrical and radiation detection characteristics of the fabricated pn- and pin-GaN detector, and pin-BGaN detector were evaluated. For electrical characteristics, CV and IV measurements were performed from room temperature (RT) to 600^{o}C. ^{241}Am α-particle source was used for radiation detection and measurement. The detector was connected to a charge-sensitive amplifier (ANSeeN Inc., ANS-CSAPA100-01-SN) using a mineral-insulated (MI) cable, and the amplifier's output pulse signals were analyzed using a multichannel analyzer (ANSeeN Inc., ANS-HSDMCA4M4N17) that simultaneously measures their detected energy and rise-time. The ^{241}Am was placed at a distance of 19 mm (incident energy to the detector of approximately 2.3 MeV after air attenuation calculated using PHITS ver.3.08, which is a Monte Carlo simulation code [4].) from the detector. The α-particles energy spectra were measured from room temperature to 450^{o}C, which is the upper limit temperature of the measurement system.

3 Results

3.1 Temperature dependence evaluation of radiation detection

Figure 1 shows the energy spectrum of ^{241}Am α-particles at each temperature using group-III nitride semiconductor detectors. In the case of a pin-BGaN diode detector, the α-particles spectrum was detected at 300^{o}C, but it was difficult to discriminate the detection signal from the noise signal at 350^{o}C. In the case of a pin-GaN detector, the α-particles spectra were detected under 450^{o}C, which is the measurement limit for this experimental setup. Furthermore, X-ray diffraction crystallinity evaluation has confirmed that BGaN crystals are less crystalline than GaN crystals. These results indicated that crystal defects in BGaN are one cause of reducing the device performance temperature. It is indicated that the pin-GaN detector is operated at even higher temperatures.

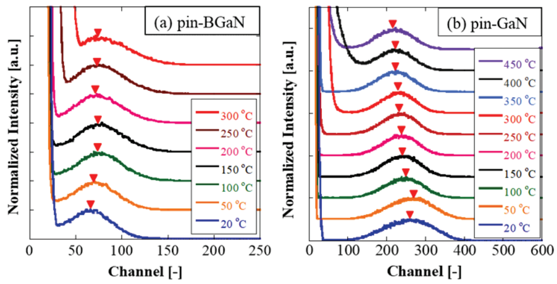

Fig.1. Energy spectra of ^{241}Am α-particles at each temperature using (a)pin-BGaN, (b)pin-GaN detector

Figure 2 shows the temperature dependence of peak position for each detector. The peak position of the energy spectrum originates from the pulse signal height of the detection signal, meaning the number of carriers excited by the α-particle. In the case of a BGaN detector, the peak position was confirmed to be constant at over 100°C. In the case of a GaN detector, a low channel shift at the peak position was confirmed over 100°C. These results indicate that the depletion layer thickness, the sensitive layer, decreased with rising temperature. The BGaN detector has a thick sensitive layer (i -BGaN layer). Therefore, BGaN is not affected by changes in the depletion layer width. It was confirmed that reducing the thick sensitive layer has a more significant effect on high-temperature tolerance.

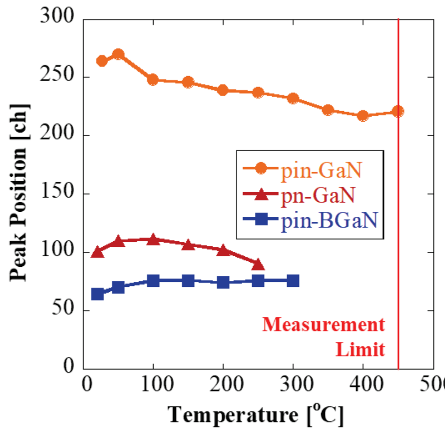

Fig. 2. Temperature-dependence of peak position for each detector

3.2 Temperature dependence of electrical characteristics

Figures 3 show the temperature dependence of leakage current at each detector. It was confirmed that the leakage current of the BGaN detector was larger than that of the GaN detector. The increase in leakage current is due to crystal defects. The significant degradation of breakdown voltage at high temperatures with large initial leakage currents suggests that crystal quality affects high-temperature tolerance.

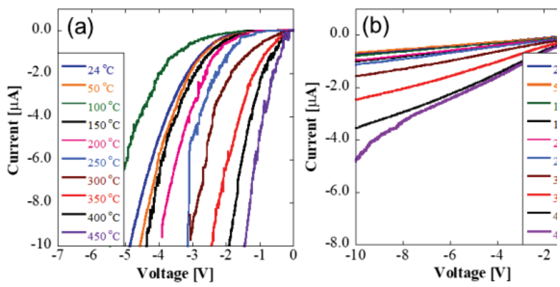

Fig. 3. Temperature dependence of leakage current at (a) pin-BGaN (7.85×10^{-4} cm^2), (b) pin-GaN detector

By temperature dependency of CV measurement, the CV curves of a pin-GaN detector at different temperatures and the temperature dependence of built-in potential are measured. Capacitance increased with rising temperature. The dielectric constant increased slightly because the bandgap decreased with rising temperature. Furthermore, a decrease in built-in potential with rising temperature was observed. This result indicates that the decrease in depletion layer width and the increase in capacitance contribute.

4 Conclusions

These results indicate that crystallinity and intrinsic layer thickness are very important with respect to high temperature tolerance of GaN and BGaN devices. In addition, the improvement of crystallinity and charge collection efficiency is a future challenge for BGaN detectors, suggesting their potential as high-temperature-compatible devices.

References

[1] T. Nakano, K. Mochizuki, T. Arikawa, H. Nakagawa, S. Usami, Y. Honda, H. Amano, A. Vogt, S. Schütt, M. Fiederle, K. Kojima, S.F. Chichibu, Y. Inoue, and T. Aoki, "Effective neutron detection using vertical-type BGaN diodes", J. Appl. Phys., **130** (2021) 124501

[2] Takayuki Nakano, "Study of group-III nitride semiconductor for novel neutron semiconducting detector", JSAP Review **2023** (2023) 230201.

[3] K. Ebara, K. Mochizuki, Y. Inoue, T. Aoki, K. Kojima, S.F. Chichibu, and T. Nakano, "Impact of growth temperature on the structural properties of BGaN films grown by metal-organic vapor phase epitaxy using trimethylboron", Jpn. J. Appl. Phys., **58** (2019) SC1042

[4] T. Sato, Y. Iwamoto, S. Hashimoto, T. Ogawa, T. Furuta, S. Abe, T. Kai, P.E. Tsai, N. Matsuda, H. Iwase, N. Shigyo, L. Sihver, and K. Niita, "Features of Particle and Heavy Ion Transport Code System PHITS Version 3.02", J. Nucl. Sci. Technol. **55** (2018) 684.

5 ACKNOWLEDGMENTS

This work was partly supported by the Joint Research for Nuclear Safety R&D Center of the Chubu Electric Power Corporation, the Cooperative Research Program of "Network Joint Research Center for Materials and Devices", Cooperative Researches at the Kindai University Reactor, the Nagoya University Institute of Materials and Systems for Sustainability Shared Use/Joint Research, Foundation for Promotion of Material Science and Technology of Japan, a Toyota Riken Scholar Grant, the Iketani Science and Technology Foundation Research Grant, MEXT Innovative Nuclear Research and Development Program Grant Number JPMXD0221459236, and the JSPS KAKENHI Grant Numbers 16H03899, 19H04394 and 23H00099 from MEXT.