Development of BGaN neutron semiconductor detector with high temperature tolerance for HTGRs

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1. Background

Neutron detection techniques

Expected to use for Nuclear instrumentation system

- High-temperature tolerance:
  New reactor temperature : FBR:500~600°C , HTGR:600~900°C
  Current neutron detector : Micro fission chamber (high-temperature tolerance : 300~500°C)
  →Difficult to use in new reactors
- Isotope irradiation tolerance : Requires tolerance of over 1 MGy

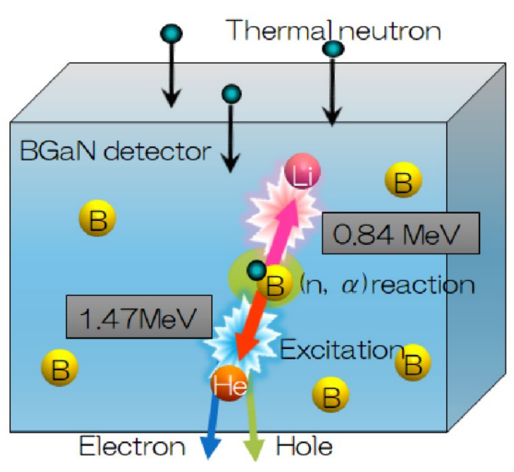
Proposal for BGaN neutron semiconductor detectors

B(BN)
Large neutron capture cross-section area

GaN
Wide-bandgap semiconductor
Low γ-rays detection sensitivity

BGaN
Neutron semiconductor detector
- Neutron are captured within BGaN
- Wide-bandgap semiconductor

Principal of neutron detector with BGaN detector



1. Neutron is captured by B atom.
2. Alpha particles are generated by $^{10}B(n,\alpha)^{7}Li$ reaction.
3. The electron-hole pairs are generated by excitation of charged particles.
4. The electric signal is detected.

$^{10}B(n,\alpha)^{7}Li$ reaction
$n + ^{10}B \rightarrow ^{7}Li\ (0.8398\ MeV) + \alpha\ (1.4721\ MeV)$

Advantages of BGaN detector

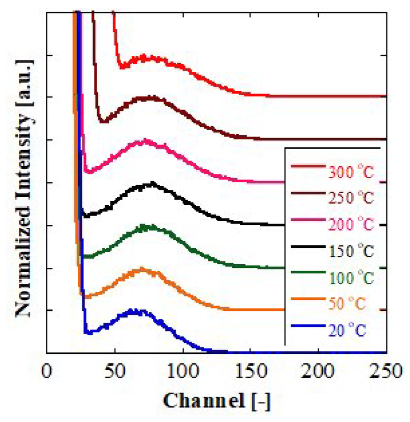
- Gamma ray sensitivity is low.
- Detection of the whole energy(2.3 MeV) for charged particles is possible.
- Low cost, large scale and small size chip fabrication is easy, because LED fabrication process is used.

2. Previous study and purpose of this study

Previous study

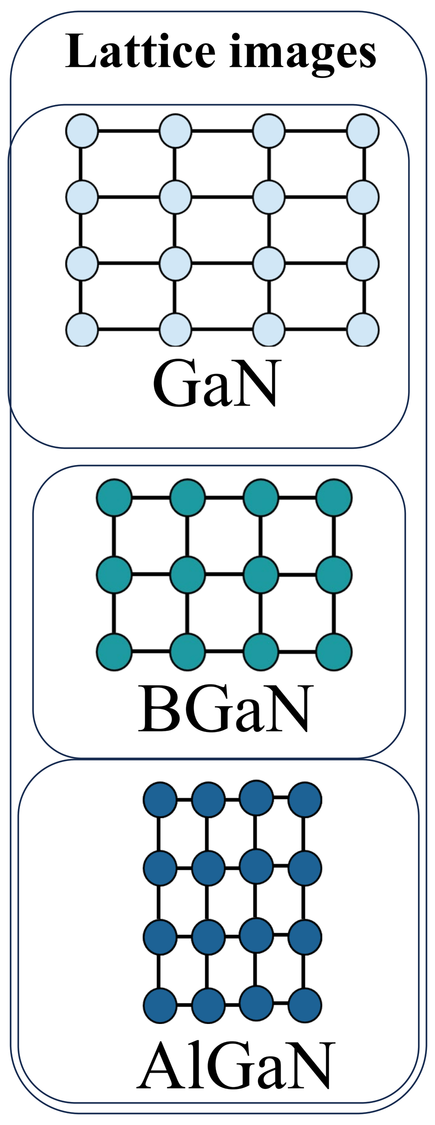
- Temperature dependence of α-particles detection using GaN diodes and BGaN diodes.[1]
- High-temperature operations
  ✓ 450 °C for a GaN detector
  ✓ 300 °C for a BGaN detector
- The cause of decreasing operation temperature of BGaN diodes are large noise signals by poor crystallinity.
  →Improving the BGaN crystallinity is necessary.

Temperature dependence of α-particles detection using BGaN diodes[1]



[1] K. Hayashi, *et al.*, IEEE. RTSD 2022

Lattice images



Conventional BGaN growth (BGaN/GaN)

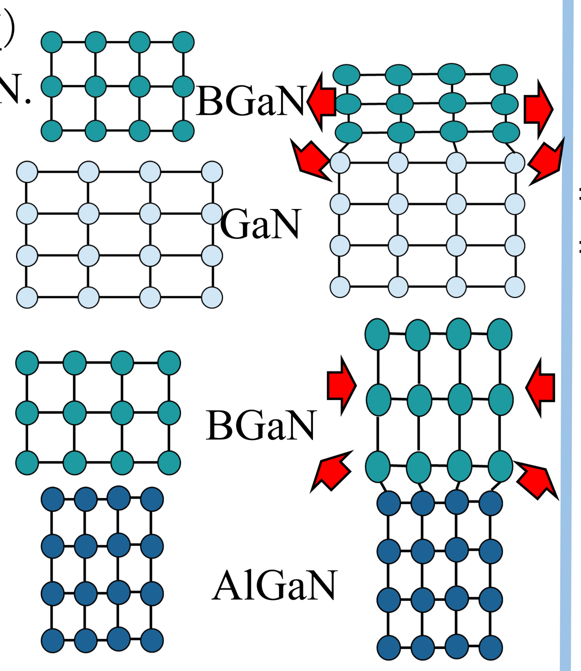
- GaN has larger lattice constant than BGaN.
- $a_{GaN} > a_{BGaN}$ Tensile strain

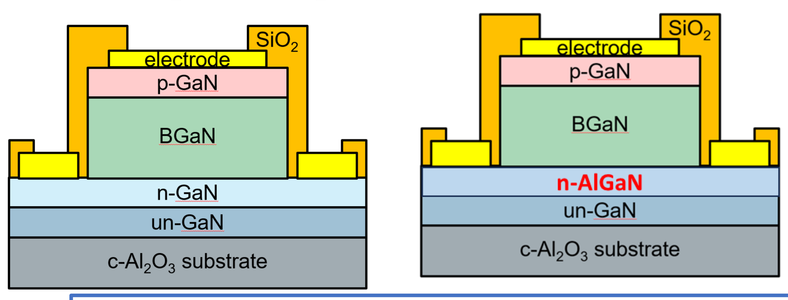
⇒Poor crystallinity due to crack generation.
High temperature tolerance is 400°C.

In this study(BGaN/AlGaN)

- Using AlGaN template.
  $a_{AlGaN} < a_{BGaN}$

→ Strain in BGaN is controlled by using strain engineering.





Purpose of this study

High temperature tolerance neutron detector using AlGaN buffer layer for strain control.
① Evaluation of crystallinity by using AlGaN
② Radiation detection characteristics

3. Experimental

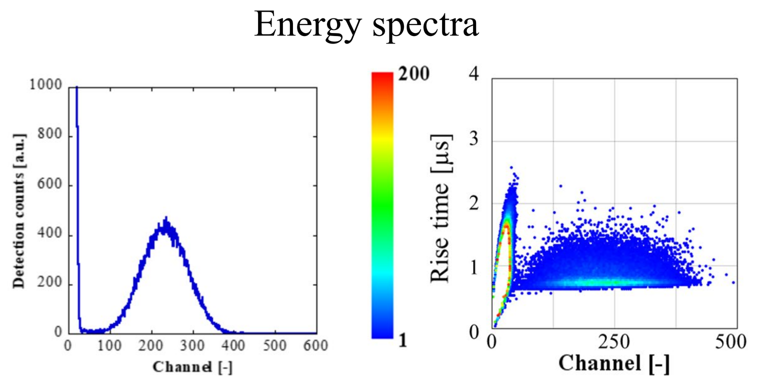
Device fabrication

Growth method : Metal Organic Vaper Phase Epitaxy (MOVPE)

Growth condition

Growth film	AlGaN	BGaN
Film thickness [μm]	1.2	1, 3, 5
Growth pressure [kPa]	20	30
Substrate temperature [°C]	1080	1000
TMB flow late [μ･mol･min-1]	-	0.09
TMAl flow late@17 °C [μ･mol･min-1]	0.45	-
Al, BN Mole fraction[%]	4~5	<0.1
substrate	Al_2O_3	

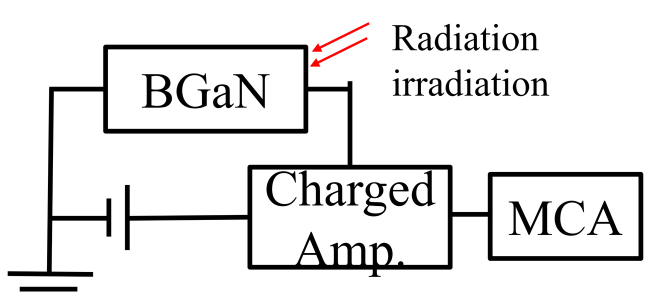
Energy spectra



channel: Pulse wave height value (detection energy)

Radiation characteristics

Radiation measurement system



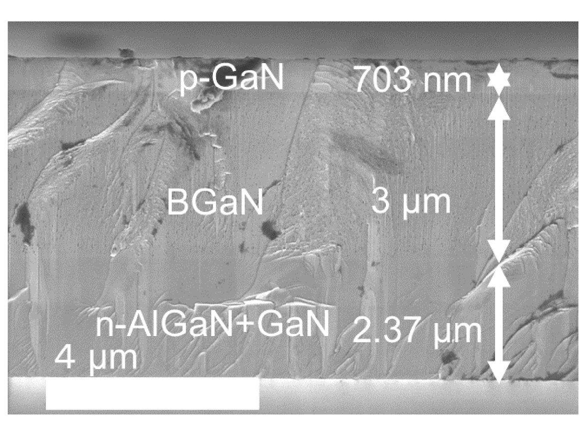
Measurement system

α-particles detection characteristics
- MCA_1: ANS-HSDMCA4M4N17 (ANSeeN Co.)
- Charged amp._1: CSP-BNC-02 (ANSeeN Co.)

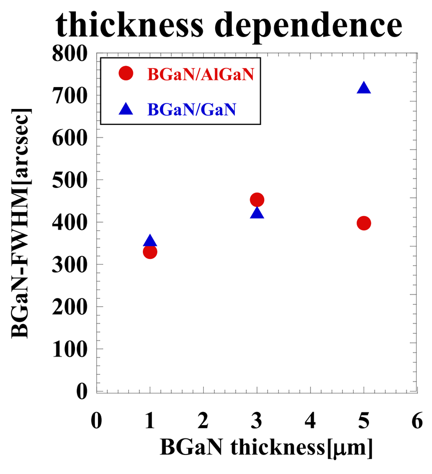
Neutron detection characteristics
- MCA_2: ANS-HSDMCA4M0N17-GF (ANSeeN Co.)
- Charged amp._2: ANS-CSAPA100-01-SN (ANSeeN Co.)

4. Structural characteristics for BGaN film

Cross sectional SEM image(3 μm)



XRC-FWHM vs BGaN film thickness dependence



✓BGaN/GaN
Crystallinity decreases with increasing film thickness.
⇒ Expanded lattice constant with GaN.

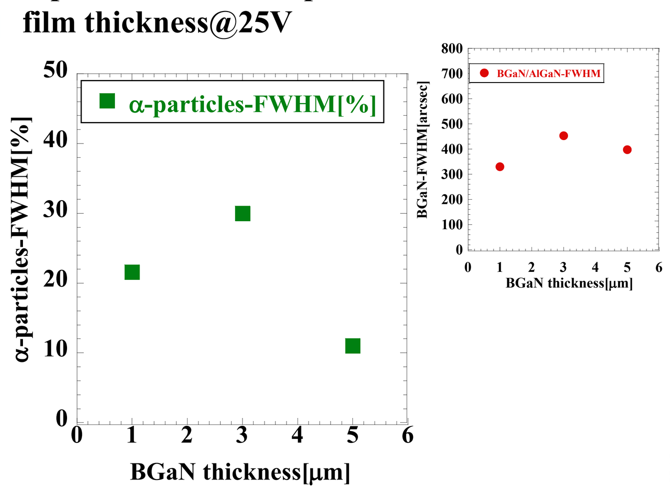
✓BGaN/AlGaN
Constant crystallinity regardless of increase in film thickness.
⇒ Reduction of lattice mismatch is suppresses strain.

Lattice relaxation suppressed and crystallinity is improved.

5. α-particles detection characteristics evaluation

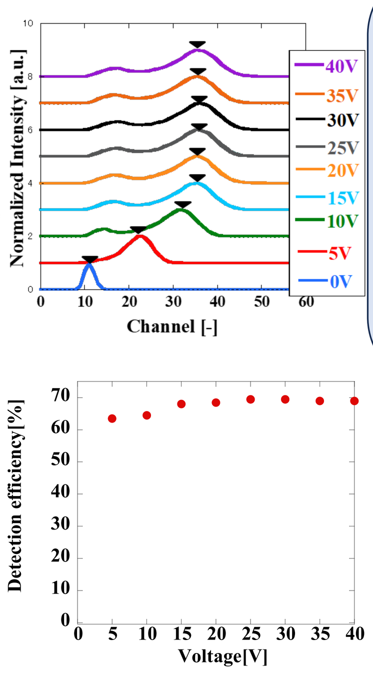
α-particles source : ^{241}Am (5.41 MeV, 3.94 MBq), Device incident energy : 2.3 MeV (distance : 1.5 cm),
Applied voltage: 0 V~ -40 V, Measurement time : 10 min

α-particles detection peak FWHM at each film thickness@25V



✓ 3 μm has the worst FWHM value.
⇒Similar trends as XRC-FWHM
⇒ **Depend on crystallinity**

Dependence of α-particles detection characteristics on applied voltage



✓α-particles peak position shifted to high channel side
⇒ **The carrier collection efficiency (CCE) was improved by increasing the applied voltage.**
✓ The peak channel position is confirmed to be stable at an applied voltage of over 20V.
⇒Whole BGaN layers become depletion layers over 20V.

Heact's equation

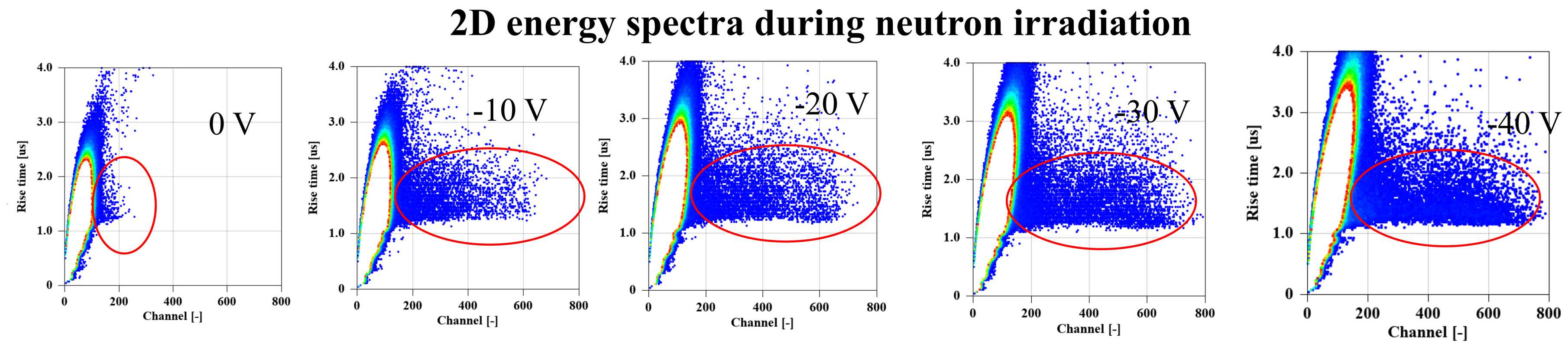
$$\mu\tau = \frac{D^2}{\ln(N_1/N_2)}\left(\frac{1}{V_2} - \frac{1}{V_1}\right)$$

✓ Mobility Lifetime Product
μτ=3.1×10-8 cm²/V･S (GaN:10-5)
⇒Due to the low carrier concentration, BGaN layer not function as a sensitized layer.

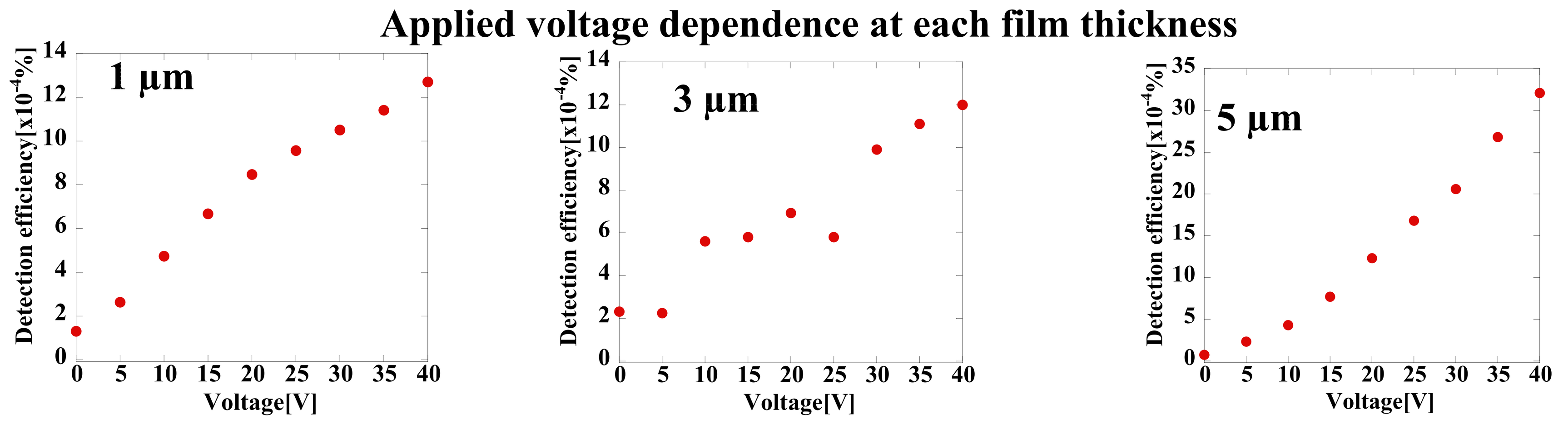
6. Neutron irradiation @ KUR (Kyoto University Research Reactor)

Rated thermal power: 1 MW (room temperature), Thermal neutron flux ≒1×10⁸ n･cm-2･min-1
Applied voltage : 0 V~ -40 V, Measurement time : 60 min

2D energy spectra during neutron irradiation



Applied voltage dependence at each film thickness

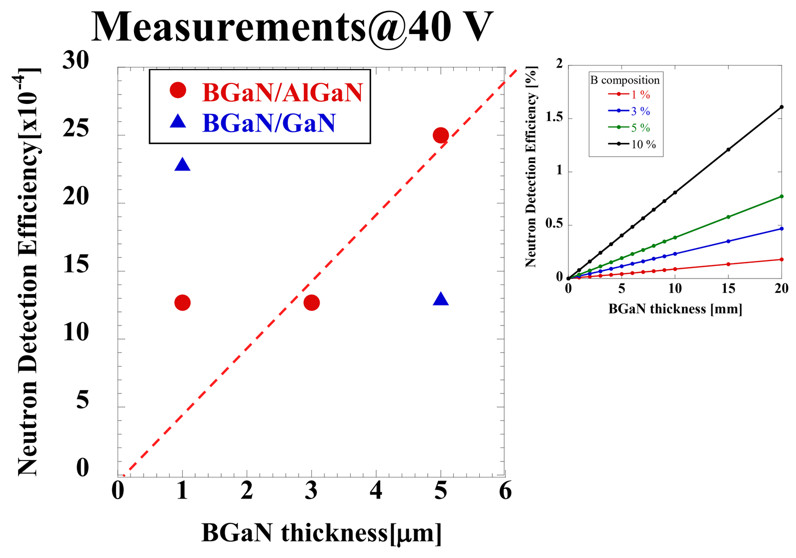


✓ Applied voltage dependence
⇒Detection efficiency increases as applied voltage increases.

Similar trend was observed for different film thicknesses.

Neutron detection efficiency at each film thickness

Measurements@40 V



✓BGaN/GaN
Neutron detection efficiency is decreased with increasing BGaN film thickness.
⇒ Deterioration of S/N ratio due to crystallinity degradation.

✓BGaN/AlGaN
Neutron detection efficiency improves with increasing film thickness.
⇒ Increasing number of B atoms capturing neutron.

✓Radiation Simulation
Proportionally high detection efficiency with thick film
⇒Proportional relationship for BGaN layer thicknesses of 3 and 5 μm.

Introduction of AlGaN buffer layer improves crystallinity of thick BGaN layer.
⇒ By increasing BGaN film thickness, neutron detection efficiency is improved.

7. Conclusion

- Lattice relaxation is suppressed by using AlGaN buffer layer, and crystallinity is improved.
- The peak channel position is confirmed to be stable at an applied voltage of over 20V.

⇒ Whole BGaN layers become depletion layers over 20V.
- The crystallinity of the thick BGaN layer is improved by the introduction of AlGaN buffer layer.

⇒ By increasing BGaN film thickness, neutron detection efficiency is improved.

8. Acknowledgments

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