

Radiation Detection with Wide- and Ultrawide-Bandgap Semiconductors: Detector Fundamentals and Performance Benchmarks for 4H-SiC, GaN, and β -Ga₂O₃

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Abstract. Wide - and ultrawide-bandgap semiconductor materials have been receiving growing attention for the application in radiation detectors for nuclear energy systems and other environments with high levels of radiation. The wide- and ultrawide-bandgap semiconductor materials have the advantages of high breakdown strength, low leakage current, and the ability to operate at elevated temperatures. In this review, the state of the art in the field of radiation detectors based on 4H-SiC, GaN, and β -Ga₂O₃ is discussed, with particular focus on the effect of the intrinsic properties of the semiconductor materials on the performance of the detectors. The parameters of particular importance for the detectors are charge collection efficiency, energy resolution, leakage current, thermal stability, and signal drift.

Among these materials, the case for 4H-SiC is the most developed, with a significant experimental base for charged particle and neutron detection, including converter-assisted detectors, as well as operation at elevated temperatures. GaN has also been found to have significant potential, especially for Schottky and vertical detectors for charged particle detection. However, its performance is often heavily dependent on the quality of the interface. β -Ga₂O₃, as a relatively new ultrawide bandgap semiconductor, is seen to have significant potential for X-ray detectors and extreme environment operation. Although many issues regarding its response to irradiation damage and its recovery after exposure are currently under investigation.

This review aims to compare these three material systems from a common perspective, thereby revealing their current capabilities as well as their most possible areas of application. A comparative summary section and an outlook section have been added to identify the main areas for future work, particularly in terms of standardized benchmarking, defect-informed device optimization, and more reliable detectors for nuclear and harsh-environment applications.

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Introduction

Among the most actively studied semiconductor platforms in this area are 4H-SiC, GaN, and β -Ga₂O₃. Each of these materials occupies a distinct position in the current detector landscape. 4H-SiC represents one of the most technologically mature WBG detector materials and has demonstrated strong performance in alpha-particle and neutron detection, including under elevated-temperature conditions. GaN has also shown promising detector behavior, particularly in vertical diode architectures, although its performance is often strongly influenced by surface and interface states as well as trap-related instabilities. β -Ga₂O₃, in contrast, is a less mature but rapidly developing UWBG semiconductor that has attracted considerable attention for X-ray detection and extreme-environment sensing, where its large bandgap and high-field capability offer clear potential advantages.

Although these materials are often discussed separately in the literature, meaningful comparison requires a common benchmarking framework. Detector performance cannot be assessed solely in terms of bandgap or nominal device architecture; instead, it depends on the combined influence of material quality, defect and trap populations, contact behavior, electric-field distribution, readout conditions, and thermal or irradiation history. Consequently, metrics such as charge-collection efficiency (CCE), energy resolution, leakage current, noise, operating temperature range, and stability under sustained exposure and bias provide a more useful basis for cross-material evaluation than isolated material parameters alone.

This review focuses on semiconductor radiation detectors based on 4H-SiC, GaN, and β -Ga₂O₃, comparing alpha/charged-particle, neutron (converter-based), and X-ray detection using unified benchmark metrics. The aim is not only to summarize detector demonstrations reported for each material system, but also to identify the main device-level and defect-related factors that govern performance and limit reproducibility. Particular attention is given to how material properties, trap physics, and detector architectures jointly determine leakage, charge collection, spectral performance, and long-term stability.

Detector fundamentals and benchmarking metrics

Signal generation and charge transport

In semiconductor radiation detectors, incident radiation deposits energy primarily through ionization and, depending on particle type and energy, also through non-ionizing interactions capable of displacing lattice atoms. For charged particles, such as α -particles, energy deposition is typically localized within a short penetration depth, whereas X-rays deposit energy more diffusely through photoelectric and Compton interactions, producing secondary electrons that generate electron-hole pairs along their trajectories. In all cases, the measurable detector signal arises from the collection of these carriers under an electric field, and detector performance is therefore governed by the balance between charge generation, carrier transport, and loss channels such as trapping and recombination.

For a deposited energy E , the number of generated electron-hole pairs may be approximated as $N \approx E/\varepsilon$, where ε is the mean energy required to create one pair. Wide- and ultrawide-bandgap semiconductors generally require a higher pair-creation energy than narrow-bandgap materials, which may reduce signal amplitude for a given deposited energy.

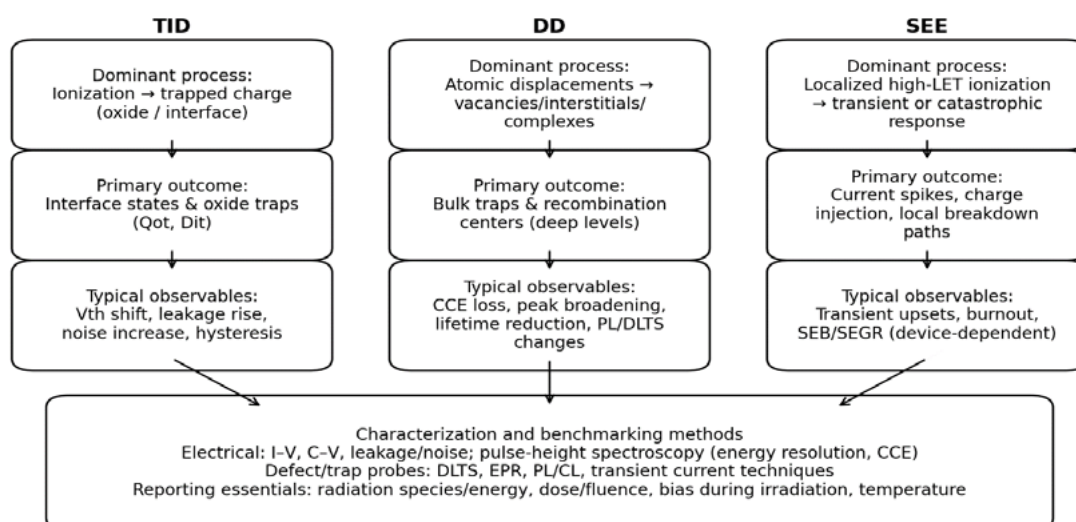


Figure 1. Unified framework for radiation detector benchmarking in wide- and ultrawide-bandgap semiconductors.

Total ionizing dose (TID) primarily introduces trapped charge in dielectrics and at interfaces, leading to threshold-voltage shifts, increased leakage, and noise degradation. Displacement damage (DD) produces vacancies, interstitials, and defect complexes that act as recombination centers and deep traps, reducing charge-collection efficiency (CCE) and broadening spectral peaks. Single-event effects (SEE), typically associated with heavy ions or highly localized energy deposition, can cause transient upsets or catastrophic failure depending on device architecture and operating bias. The diagram links these mechanisms to detector-relevant observables (CCE, energy resolution, leakage/noise, stability) and to commonly used characterization methods (I-V/C-V, pulse-height spectroscopy, DLTS/EPR/PL), enabling consistent cross-material comparisons for 4H-SiC, GaN, and β -Ga₂O₃ detectors.

Benchmark metrics: what should be reported and compared

To compare detectors across 4H-SiC, GaN, and β -Ga₂O₃ in a consistent way, the following metrics are the most informative:

1. Charge-collection efficiency (CCE).

CCE quantifies what fraction of the generated charge is collected at the electrodes. It can be inferred from pulse height relative to an expected full-energy peak, or from calibration with known sources.

2. Energy resolution (FWHM) and peak shape.

Energy resolution is typically expressed as the full width at half maximum (FWHM) of a spectral peak, sometimes as an absolute energy (keV) or relative percentage.

3. Leakage current density and noise.

Leakage current increases shot noise and limits achievable resolution, especially at elevated temperatures.

4. Active volume, depletion width, and operating bias.

Because many published demonstrations use different thicknesses, doping levels, and bias points, an “apples-to-apples” comparison requires explicit reporting of device geometry and the bias used to reach the reported performance.

5. Temperature range and stability under operating conditions.

A central motivation for SiC, GaN, and β -Ga₂O₃ detectors is their potential for high-temperature operation.

6. Radiation tolerance and performance retention.

Since detector environments may include sustained irradiation, the review distinguishes between *detector function* (ability to measure radiation) and *radiation hardness* (ability to maintain performance metrics under accumulated dose/fluence).

Defects, traps, and polarization: why defect physics enters a detector review

In real detectors, defects and interfaces influence performance in two strongly coupled ways. First, they act as trapping and recombination centers that reduce charge-collection efficiency and broaden spectral peaks. Second, trap charging may distort the internal electric field over time, leading to gain changes, peak shifts, hysteresis, and other polarization-related phenomena. These effects become more pronounced at high electric fields, elevated temperatures, and after irradiation, and they are strongly dependent on both material system and processing history.

For SiC and GaN, the literature already provides relatively mature links between device degradation and specific trap families or interface-related effects. For β -Ga₂O₃, such defect-metric relationships are still being established, although recent irradiation and recovery studies already indicate that defect evolution may play a significant role in detector stability. Consequently, defect and trap physics must be treated as an integral part of detector benchmarking rather than as a separate materials issue.

Table 1. Recommended benchmarking metrics for semiconductor radiation detectors and their dominant limiting factors.

Metric (report)	How it is measured	Why it matters	Typical limiting factors	Notes for fair comparison
Charge-collection efficiency (CCE)	Pulse-height spectroscopy vs known energy; relative peak position; calibration source	Measures how much charge is generated and collected	Bulk traps, recombination, insufficient field/depletion, polarization	Always report bias, thickness, doping (or depletion width)
Energy resolution (FWHM)	FWHM of full-energy peak (keV or %)	Captures statistical + electronic noise + collection nonuniformity	Leakage/shot noise, capacitance, trap-induced broadening, dead layers	Report shaping time, electronics chain, temperature
Leakage current density	I–V under reverse bias; often vs temperature	Strongly controls noise and high-T operation	Surface leakage, contact leakage, interface traps, and generation currents	Report device area and passivation; normalize to area
Noise / ENC (if available)	Equivalent noise charge or baseline RMS	Allows cross-lab comparison of readout limitations	Leakage, capacitance, electronics, microphonics	Provide preamp type, shaping, bandwidth
Active volume / depletion width	C–V extraction; thickness; bias at operation	Determines interaction volume and collection time	Doping, breakdown limit, geometry	Provide thickness and C–V or estimated W(V)

Metric (report)	How it is measured	Why it matters	Typical limiting factors	Notes for fair comparison
Operating bias / field	Reverse bias at measurement; breakdown margin	Governs drift time and trapping probability	Breakdown, field crowding, surface effects	Specify edge termination/field plates if used
Temperature range	Resolution/CCE/leakage vs T	Key advantage of WBG/UWBG detectors	Leakage activation, trap kinetics, contact stability	Report stabilization time and thermal setup
Stability / drift	Peak position vs time under bias; repeated cycles	Indicates polarization and long-term reliability	Trap charging, interface states, space-charge buildup	Report time scale and bias history
Radiation tolerance / retention	Metrics before/after dose/fluence steps	Needed for nuclear/harsh environments	Accumulated traps/defects, contact degradation	Report radiation type/energy/fluence, bias during irradiation
Neutron detection efficiency (converter-based)	Count rate vs source/flux; efficiency modeling	System-level metric (converter + detector)	Converter thickness, reaction product escape, interface losses	Must report converter material/thickness and geometry

4H-SiC radiation detectors

Why 4H-SiC is a mature detector platform

4H-SiC is one of the most established wide-bandgap materials for semiconductor radiation detectors owing to its high breakdown field, good thermal conductivity, and the relatively advanced state of epitaxial growth and device processing. For detector applications, these properties translate into the ability to sustain high electric fields with comparatively low leakage current, thereby enabling stable charge collection and reduced electronic noise, including under elevated-temperature conditions. As a result, 4H-SiC has been extensively investigated for charged-particle detection, particularly α -particle spectroscopy, as well as for neutron detection using converter layers. [1]

Device architectures used for detection in 4H-SiC

The dominant device architecture in the 4H-SiC detector literature is the reverse-biased Schottky barrier diode fabricated on epitaxial layers, often combined with edge termination and surface passivation to suppress premature breakdown and surface leakage. The main advantages of SBD-based detectors include relatively simple fabrication, low capacitance, and compatibility with thick epitaxial layers that support appreciable depletion widths. [2]

Alpha and charged-particle detection in 4H-SiC

Most 4H-SiC charged-particle detectors are implemented as reverse-biased Schottky barrier diodes on n-type epitaxial layers. Under reverse bias, a depletion region forms beneath the Schottky contact, and incident α -particles deposit their energy within a shallow depth near the detector surface, generating electron-hole pairs that are collected by drift under the internal electric field. In this configuration, spectral performance is determined primarily by two factors: the completeness and uniformity of charge collection, and the electronic noise floor, which is strongly influenced by leakage current and detector capacitance. [3]

Neutron detection with converter-coupled 4H-SiC detectors

Neutron detection using 4H-SiC is most commonly achieved through converter layers, such as ${}^6\text{LiF}$ or ${}^{10}\text{B}$ -containing films, deposited on or coupled to the detector surface. Neutron capture reactions within the converter generate energetic charged products that enter the SiC detector and produce ionization signals. This configuration enables thermal neutron sensitivity while taking advantage of the high-field, low-leakage operation of 4H-SiC, including under harsh environmental conditions. [4]

Performance-limiting factors: leakage, trapping, and stability

First, surface leakage and edge-field management strongly influence detector performance. Surface conduction pathways and electric-field crowding near device edges may dominate leakage current and baseline noise, thereby limiting high-bias operation and degrading energy resolution. Passivation quality and edge termination, therefore, play a major role in high-field detector stability.

Second, bulk trapping and charge-collection nonuniformity may limit spectral quality even in nominally high-quality epitaxial material. Deep levels arising from native defects, irradiation-induced defects, or process-related damage can reduce charge-collection efficiency and broaden spectral peaks. In addition, trap occupancy dynamics may cause time-dependent behavior such as peak drift or hysteresis under sustained bias.

Third, contact and barrier non-idealities contribute significantly to leakage and its temperature dependence. Barrier inhomogeneity, interfacial reactions, or metallurgical instability may increase leakage current and degrade noise performance, especially under elevated-temperature operation.

*GaN radiation detectors**Scope of GaN detector literature within this review*

Compared with 4H-SiC, the GaN radiation-detector literature is narrower, but it includes several important demonstrations that are directly relevant for detector benchmarking. In the present review, GaN is considered primarily as a platform for charged-particle detection, particularly α -particle detection, using diode-based device structures. Its relevance arises from the combination of a wide bandgap and detector architectures, especially Schottky and vertical diodes, capable of supporting depletion-based operation. [5]

Device architectures: Schottky and vertical GaN-on-GaN diodes

Most GaN detector demonstrations are based on reverse-biased Schottky barrier diodes or vertical GaN-on-GaN diode structures. In depletion-based operation, the achievable active volume is determined mainly by doping and layer thickness, whereas the noise floor is governed by leakage current and capacitance. Many studies emphasize that sufficient depletion width at moderate reverse bias is essential for improving charge collection and peak formation, particularly in α -particle detection, where the deposited energy is relatively localized but still benefits from a uniform electric field and low trapping. [6]

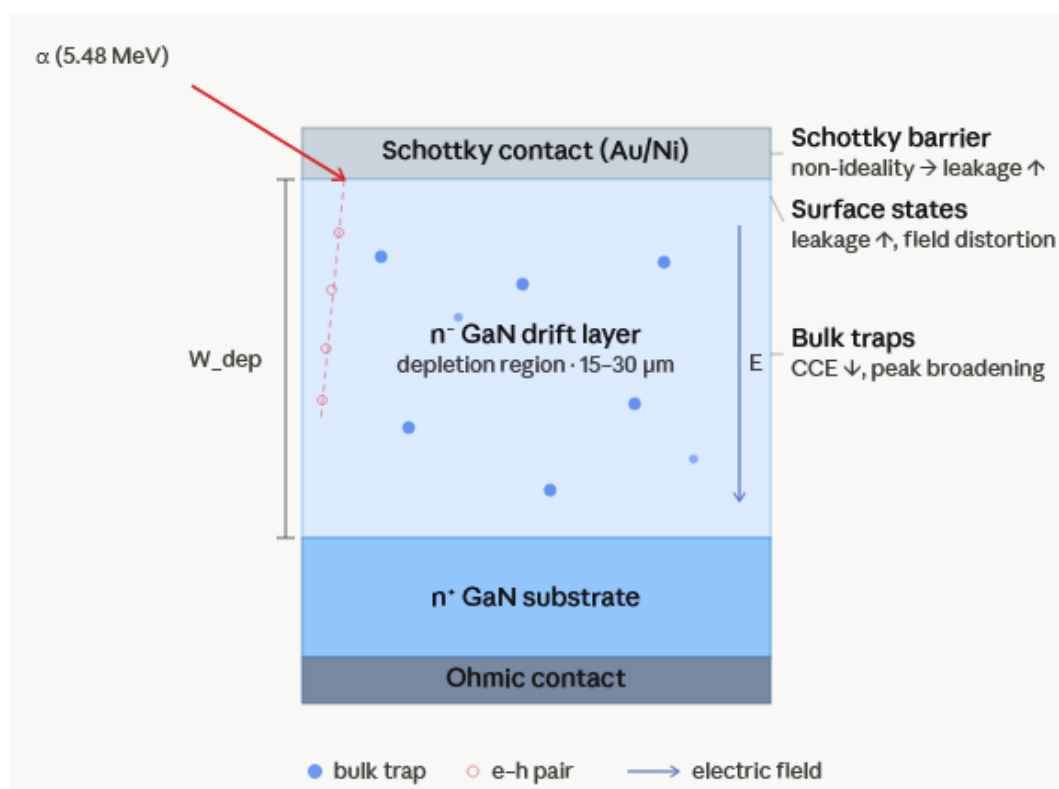


Figure 2. Vertical GaN-on-GaN SBD radiation detector: layer structure and dominant performance-limiting channels.

Alpha and charged-particle detection: performance metrics and trends

GaN α -particle detectors are typically characterized through pulse-height spectra, peak identification, and energy resolution under reverse bias. As in 4H-SiC detectors, the primary objectives are to maximize charge collection while minimizing leakage-driven noise in order to obtain stable and narrow peaks. However, the GaN detector literature places particular emphasis on the role of depletion width, surface quality, and interface control in determining whether satisfactory detector performance can be achieved.

Several recurring trends may be identified across reported GaN detector demonstrations. Increasing reverse bias generally improves peak formation by widening the depletion region and shortening carrier transit time, although usable bias range may be limited by breakdown risk and surface leakage. Leakage current, together with its temperature dependence, often becomes the dominant contributor to the electronic noise floor, which makes contact engineering and surface passivation particularly important. In addition, time-dependent changes in peak position, peak width, or baseline level are often associated with trap charging and detrapping, especially in structures where surface and interface effects strongly affect the internal field distribution. [7]

Limiting factors: traps, surfaces, and contact stability

GaN detector performance is frequently constrained by factors that are closely linked to surfaces, interfaces, and trap populations.

First, surface and interface states may increase surface leakage, distort local electric fields near contact edges, and introduce slow response components that manifest as drift or hysteresis during sustained operation.

Second, bulk and buffer traps may contribute to carrier trapping and peak broadening, especially when the depletion region extends into regions of lower structural or electronic quality. Their influence may depend strongly on growth route, substrate choice, and epitaxial design. [7]

Third, Schottky barrier non-idealities may elevate leakage current and reduce stability, especially at higher temperatures. Barrier inhomogeneity, contact reactions, or interfacial degradation may therefore limit the usable bias window and degrade detector resolution through increased noise.

β -Ga₂O₃ radiation detectors*Why β -Ga₂O₃ is positioned as the UWBG X-ray opportunity*

Within the WBG/UWBG detector landscape, β -Ga₂O₃ is generally regarded as less technologically mature than 4H-SiC and GaN, but particularly promising for X-ray detection. In the detector literature, 4H-SiC and GaN are more commonly associated with mature alpha-particle and neutron detector demonstrations, whereas β -Ga₂O₃ is increasingly highlighted as an emerging ultrawide-bandgap platform for X-ray sensing. This distinction provides a natural basis for the present comparison: 4H-SiC and GaN are treated as mature reference platforms, while β -Ga₂O₃ is evaluated mainly through the lens of X-ray detector performance, stability, and extreme-environment potential.

Device concepts used for β -Ga₂O₃ radiation detection

The β -Ga₂O₃ detector literature is dominated primarily by two device concepts: Schottky barrier diodes (SBDs) and metal–semiconductor–metal (MSM) structures. SBD detectors operate in a depletion-controlled regime and are therefore naturally comparable to SiC- and GaN-based diode detectors through parameters such as leakage current, depletion width, bias stability, and, when available, spectroscopic performance. In contrast, MSM and photoconductor-like devices are more frequently used in X-ray current-mode detection, where reported sensitivity may be high but the observed response is often strongly affected by trap-related gain, contact behavior, and slow recovery effects. Accordingly, the benchmarking metrics introduced in Section 2 should be interpreted with attention to the operating mode of the detector, since pulse-mode and current-mode devices emphasize different aspects of performance.

X-ray detection: performance metrics and benchmarking criteria

β -Ga₂O₃ detector studies reported in the literature primarily emphasize X-ray sensing performance, including sensitivity, response stability, linearity, and response time. Unlike reports on alpha particle detectors, where energy resolution is often the dominant indicator, X-ray studies of β -Ga₂O₃ often focus on the characterization of the current regime and dose rate dependence. Accordingly, a reliable comparison of the results of studies using β -Ga₂O₃ X-ray detectors requires consistent information about the device structure, geometry, operating displacement, temperature, X-ray spectrum or energy range, dose rate and the corresponding response rate. Stability-related characteristics such as hysteresis, afterglow, baseline offset, and recovery time should be considered as important parameters for comparative analysis, rather than as secondary observations. [8] This distinction is important because apparent sensitivity enhancements may, in some device concepts, arise from trap-mediated gain and therefore may not directly correspond to improved detector fidelity or long-term reproducibility.

Defects, irradiation response, and stability considerations

A central issue in β -Ga₂O₃ radiation detectors is the strong influence of defects and defect-related recovery processes on device stability. Irradiation and implantation studies indicate that damage accumulation may induce phase-related structural signatures and that recovery behavior depends sensitively on both damage level and annealing temperature. These observations are important for detector interpretation because they imply that β -Ga₂O₃ device response may depend not only on nominal device design, but also on material history, thermal cycling, and prior exposure conditions. In practical detector terms, such effects may appear as drift, hysteresis, slow stabilization, or changes in baseline response. For this reason, β -Ga₂O₃ detector studies should explicitly report exposure history, bias conditions, and recovery protocols when discussing sensitivity and long-term stability.

*Cross-material comparison (4H-SiC vs GaN vs β -Ga₂O₃)**Comparison logic and scope*

This section synthesizes detector demonstrations across 4H-SiC, GaN, and β -Ga₂O₃ using the unified benchmarking metrics defined in Section 2 (Table 1). The comparison is explicitly radiation-detection-focused (signal formation and detector performance), not a general radiation-hardness survey. Consistent with the detector-focused framing in the literature, 4H-SiC and GaN are treated as the more mature platforms for alpha/charged-particle and neutron (converter-based) detection, while β -Ga₂O₃ is evaluated primarily in the context of X-ray detection and extreme-environment opportunities.

Table 2. Cross-material evidence table for WBG/UWBG radiation detectors.

Material	Radiation modality	Device structure	Key conditions (bias, temperature, geometry)	Main reported metric	Stability / drift observations	Main limiting factor	Reference
4H-SiC	Alpha / charged particles	Schottky barrier diode (epitaxial)	up to 500 °C; high-quality epitaxial detector; reverse current from 1 pA (RT) to 10 nA (500 °C)	Energy resolution worsened by only ~20% from RT to 500 °C	High-temperature operation demonstrated; detailed long-term drift not reported	Temperature-driven leakage increase; contact/barrier stability	[1]
4H-SiC	Alpha / charged particles	Epitaxial Schottky detector	operating bias -90 V; large-area epitaxial detector	Energy resolution 0.29% for uncollimated 5.48 MeV α ; leakage current 3.5 pA	not reported	Deep levels and contact/topography-related collection losses	[2]
4H-SiC	Neutrons (converter-based)	Large-area SBD + 6LiF converter	epithermal neutron column; neutron fluence 10^9 – 10^{13} cm ⁻²	Neutron response demonstrated via α and triton peaks	not reported	Converter thickness / geometry and system-level efficiency definition	[3]
4H-SiC	Neutrons (converter-based)	Large-area SBD + 6LiF or 10B4C converter	1×1 mm ² and 5×5 mm ² diodes; 6LiF thickness 26.54 μ m for best case	Thermal neutron efficiency up to 5.02% with 6LiF	Temperature-dependent α response also reported; full drift analysis not reported	Converter choice/thickness; diode area; leakage at larger area	[4]
GaN	Alpha / charged particles	Bulk GaN Schottky detector	freestanding n-type bulk GaN; leakage current 7.53 ± 0.3 nA at 200 V; 5.486 MeV α source	Energy resolution $2.2 \pm 0.2\%$ at 5.486 MeV under 550 V	not reported	Need for large depletion depth / relatively high bias	[5]

Material	Radiation modality	Device structure	Key conditions (bias, temperature, geometry)	Main reported metric	Stability / drift observations	Main limiting factor	Reference
GaN	Alpha / charged particles	GaN-on-GaN Schottky diode	15 μm compensated drift layer; -20 V ; 5.48 MeV α source	CCE $\approx 65\%$ at -20 V	Lower variation of CCE with bias than earlier GaN devices	Residual carrier density / limited depletion width at low bias	[6]
GaN	Alpha / charged particles	Vertical GaN-on-GaN Schottky diode	30 μm drift layer; -300 to -750 V ; 5.48 MeV α source	CCE 96.7% at -300 V ; up to 100% at -750 V ; spectral resolution 71 keV reported in the low-voltage detector study	Improved bias robustness reported; detailed long-term drift not reported	Surface/interface trapping and bias-dependent depletion control	[6]
GaN	Particle irradiation tolerance relevant to detectors	Schottky pad / guard-ring structures	proton and 1 MeV neutron irradiation to SLHC-type fluences	Pre-/post-irradiation I-V and CCE used to assess radiation hardness	Leakage remained several orders lower than Si after irradiation	Radiation-induced defects, but overall, strong hardness for particle environments	[7]
$\beta\text{-Ga}_2\text{O}_3$	X-rays	Bulk-substrate Schottky barrier diode	bulk (100) $\beta\text{-Ga}_2\text{O}_3$ substrate	Photo-to-dark current ratio >800 in X-ray detection	not reported	Dark current / contact quality	[8]
$\beta\text{-Ga}_2\text{O}_3$	X-rays	$\beta\text{-Ga}_2\text{O}_3\text{:Fe}$ single-crystal detector with vertical Ti/Au electrodes	high-resistivity Fe-doped crystal ($>10^{12}\ \Omega\cdot\text{cm}$)	Sensitivity $75.3\ \mu\text{C Gy}^{-1}\text{air}^{-1}\text{cm}^{-2}$; response time 0.2 s; SNR ~ 100	Good short-term stability reported in the detector paper	Trap-mediated dynamics / material compensation control	[9]

Summary comparison: current strengths of each material platform

4H-SiC currently provides the most balanced platform for alpha-particle detection and converter-based neutron detection, combining strong spectroscopy-oriented performance with demonstrated operation in harsh and elevated-temperature environments. Its main practical advantage is stable depletion-based operation together with comparatively favorable leakage and noise characteristics under demanding conditions.

GaN represents a strong platform for charged-particle detection, particularly in vertical and GaN-on-GaN diode architectures. However, its detector performance and long-term stability are often more strongly influenced by surface and interface states, trap-related effects, and depletion-width control, making device processing and passivation especially important.

β -Ga₂O₃ appears most promising for X-ray detection, where its ultrawide-bandgap character and high-field capability support extreme-environment sensing concepts. At the same time, defect and trap populations, as well as recovery and thermal history, can significantly influence drift, hysteresis, and repeatability. For this reason, stability-related parameters should be treated as key benchmarking outputs in β -Ga₂O₃ detector studies.

Common gaps and reporting limitations in the literature

Despite substantial progress across all three material platforms, meaningful cross-paper comparison is often limited by incomplete or inconsistent reporting. The most common sources of comparison uncertainty include incomplete information on device geometry and depletion width, insufficient reporting of bias conditions during measurement and irradiation/exposure, unclear temperature stabilization procedures, and the absence of systematic drift or time-stability data. For neutron detectors, converter thickness and efficiency definitions are not always reported in a directly comparable way, while in X-ray detector studies, the incident spectrum and dose-rate calibration method may also differ significantly across publications.

Roadmap for next-generation WBG/UWBG radiation detectors

The cross-material comparison presented in Section 6 reveals that the principal barrier to progress is not the absence of promising detector demonstrations, but rather the difficulty of comparing them reliably and translating laboratory results into reproducible device performance. The roadmap proposed here, therefore, focuses on three concrete directions: closing measurement gaps, coupling defect characterization to detector outcomes, and defining the experiments most likely to generate field-wide impact.

Closing measurement and reporting gaps.

The most immediate priority is the adoption of the minimum reporting set defined in Section 2 as a community standard. At present, a significant fraction of published detector studies omit at least one parameter — most often depletion width, bias history, or time-dependent stability data — that is necessary for meaningful cross-paper comparison. For β -Ga₂O₃ X-ray detectors specifically, time-dependent response traces and recovery protocols after irradiation should be treated as mandatory outputs rather than supplementary observations, given the strong influence of trap-mediated dynamics on apparent sensitivity. For converter-based neutron detectors, efficiency definitions and converter geometry must be reported consistently to enable system-level comparison across different designs.

Defect-to-performance coupling.

Across all three platforms, the link between specific trap populations and measurable detector degradation remains incompletely established. For 4H-SiC, the correlation between the $Z_1/2$ deep level and CCE loss under prolonged bias is relatively well documented, but equivalent defect-metric relationships for GaN interface traps and β -Ga₂O₃ irradiation-induced defects are still emerging. Closing this gap requires that detector-level measurements (CCE, FWHM drift, leakage evolution) be performed in parallel with defect-sensitive characterization — DLTS, photoluminescence, or EPR where applicable — rather than as separate materials and device studies. This coupling is particularly urgent for β -Ga₂O₃, where recovery behavior after irradiation is already known to be strongly defect-dependent but has not yet been systematically connected to detector stability metrics.

High-value experiments.

Four categories of experiments would provide the greatest impact for future cross-material benchmarking:

1. *Modality-standardized round-robin tests* — alpha-particle spectroscopy with a common ^{241}Am source, converter-based neutron detection at a reference thermal flux, and X-ray dose-rate response using a defined spectrum — performed on representative devices from each material platform under identical readout conditions. Even a limited inter-laboratory comparison of this type would significantly reduce the ambiguity currently arising from inconsistent measurement protocols.

2. *Temperature-stability maps* — systematic measurements of leakage current, CCE or sensitivity, and peak or signal drift as a function of operating temperature under fixed bias, reported for all three platforms using equivalent thermal stabilization procedures. Such data are essential for evaluating the high-temperature advantage that motivates WBG/UWBG detector research, yet remain sparse in the current literature.

3. *Bias-history and recovery protocols* — controlled experiments in which pre-biasing duration, post-exposure relaxation time, and annealing temperature are varied systematically and correlated with changes in CCE, FWHM, and baseline current. For $\beta\text{-Ga}_2\text{O}_3$ current-mode detectors in particular, this class of experiment is prerequisite for distinguishing genuine sensitivity from trap-gain artifacts.

4. *Radiation-sequential benchmarking* — measurement of the full detector metric set (leakage, CCE, energy resolution or sensitivity) before and after defined irradiation steps, with intermediate annealing checks, to separate reversible trap charging from permanent displacement damage. This protocol would provide directly comparable radiation-tolerance data across 4H-SiC, GaN, and $\beta\text{-Ga}_2\text{O}_3$ and is currently absent from most published studies.

Together, these directions would convert the benchmarking framework established in Section 2 from a reporting standard into an active experimental program, generating the comparative evidence base needed to guide materials selection and device engineering for nuclear instrumentation and harsh-environment sensing applications.

Conclusion

This review has compared radiation detection based on 4H-SiC, GaN, and $\beta\text{-Ga}_2\text{O}_3$ using a unified benchmarking framework centered on charge collection efficiency, energy resolution or sensitivity, leakage and noise, temperature capability, and stability under sustained exposure.

Within the current state of the literature, 4H-SiC stands as the most mature platform, being the only material system with repeated demonstrations of spectroscopy-grade alpha-particle detection and converter-based neutron sensing under elevated-temperature conditions exceeding 300 °C. GaN provides a credible alternative for charged-particle detection in vertical diode architectures, though its practical performance is often limited by surface states, trap-related instabilities, and depletion-width control — factors that are strongly process-dependent rather than intrinsic. $\beta\text{-Ga}_2\text{O}_3$, while less mature, represents the most promising ultrawide-bandgap candidate for X-ray detection and extreme-environment operation, with demonstrated sensitivity values competitive with other semiconductor platforms; however, its dominant challenge remains stability and reproducibility under sustained bias and irradiation.

The overarching conclusion across all three platforms is that detector performance is determined not only by bandgap advantages, but — often more critically — by device architecture, interface quality, and defect and trap dynamics that govern long-term stability. Thus, progress in this area will require standardized reporting of time-dependent behavior, the development of defect-aware devices, and protocols for comparative analysis of various materials that allow for objective comparisons under equivalent measurement conditions. These steps are prerequisites for the transition of any of the three platforms from laboratory demonstrations to reliable use in nuclear instruments and sensing in harsh environments.

The contribution of the authors

Nalibay K. – conceived the review framework; performed the literature search and selection; carried out the critical analysis and synthesis of the reviewed study; prepared all tables/figures; wrote the original draft; revised and finalized the manuscript.

Amangeldi N. – provided scientific supervision; reviewed the manuscript and contributed to editing; approved the final version.

Conflict of Interest

The authors declare that they have no conflict of interest related to the publication of this article.

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Кең және аса кең тыйым салынған аймаққа ие жартылай өткізгіштер негізіндегі сәулеленуді анықтау: 4H-SiC, GaN және β -Ga₂O₃ үшін детекторлардың жұмыс негіздері мен салыстырмалы сипаттамалары

Аңдатпа. Кең және аса кең тыйым салынған аймаққа ие жартылай өткізгіш материалдар ядролық энергетика жүйелеріне арналған радиациялық детекторларда және радиация деңгейі жоғары ортада қолданылуына байланысты жоғары қызығушылық тудыруда. Мұндай материалдардың артықшылықтарына жоғары электрлік беріктік, төмен ағып кету тогы және жоғары температура жағдайында жұмыс істеу қабілеті жатады. Бұл шолуда 4H-SiC, GaN және β -Ga₂O₃ негізіндегі радиациялық детекторлар саласындағы

қазіргі зерттеу деңгейі қарастырылып, жартылай өткізгіш материалдардың ішкі қасиеттерінің детектор сипаттамаларына әсеріне ерекше назар аударылады. Детекторлар үшін маңызды параметрлерге заряд жинау тиімділігі, энергия бойынша ажырату қабілеті, ағып кету тогы, жылулық тұрақтылық және сигналдың дрейфі жатады.

Аталған материалдардың ішінде 4H-SiC ең жетілген материал болып табылады; ол үшін зарядталған бөлшектер мен нейтрондарды тіркеу, соның ішінде конвертер қолданылатын детекторлар және жоғары температура жағдайындағы жұмыс бойынша ауқымды эксперименттік база жинақталған. GaN материалы да, әсіресе Шоттки типті және вертикаль құрылымды детекторлар үшін, зарядталған бөлшектерді анықтауда айтарлықтай әлеует көрсетеді. Алайда оның жұмыс сипаттамалары көбіне интерфейс сапасына тәуелді болады. β -Ga₂O₃ салыстырмалы түрде жаңа аса кең тыйым салынған аймақты жартылай өткізгіш ретінде рентгендік детекторлар мен экстремалды ортада қолдану үшін перспективалы материал болып саналады. Дегенмен, сәулелену әсерінен болатын зақымдануларға төзімділігі және сәулеленуден кейін қалпына келу қасиеттеріне қатысты көптеген мәселелер әлі де зерттелу үстінде.

Бұл шолудың мақсаты — осы үш материалдық жүйені ортақ көзқарас тұрғысынан салыстырып, олардың қазіргі мүмкіндіктері мен болашағы зор қолдану салаларын анықтау. Болашақ зерттеу бағыттарын белгілеу үшін салыстырмалы қорытынды және даму перспективасы бөлімдері енгізілген. Әсіресе стандартталған бенчмаркинг әдістері, ақауларды ескере отырып құрылғыларды оңтайландыру және ядролық әрі экстремалды орта жағдайларына арналған сенімді детекторлар жасау мәселелеріне назар аударылған.

Түйін сөздер: 4H-SiC, GaN, β -Ga₂O₃, кең тыйым салынған аймақты жартылай өткізгіштер, аса кең тыйым салынған аймақты жартылай өткізгіштер.

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Детектирование излучения с использованием полупроводников с широкой и сверхширокой запрещённой зоной: основы работы детекторов и сравнительные характеристики 4H-SiC, GaN и β -Ga₂O₃

Аннотация. Полупроводниковые материалы с широкой и сверхширокой запрещённой зоной привлекают всё больше внимания для применения в радиационных детекторах для систем ядерной энергетики и других сред с высоким уровнем радиации. Такие материалы обладают рядом преимуществ, включая высокую электрическую прочность, низкий ток утечки и способность работать при повышенных температурах. В данном обзоре рассматривается современное состояние исследований в области радиационных детекторов на основе 4H-SiC, GaN и β -Ga₂O₃ с особым акцентом на влияние внутренних свойств полупроводниковых материалов на характеристики детекторов. Наиболее важными параметрами для детекторов являются эффективность сбора заряда, энергетическое разрешение, ток утечки, термическая стабильность и дрейф сигнала.

Среди этих материалов наиболее развитым является 4H-SiC, для которого накоплена значительная экспериментальная база по детектированию заряженных частиц и нейтронов, включая детекторы с использованием конвертеров, а также работу при повышенных температурах. GaN также демонстрирует значительный потенциал, особенно для детекторов Шоттки и вертикальных структур, предназначенных для регистрации заряженных частиц. Однако его характеристики часто существенно зависят от качества интерфейса. β -Ga₂O₃ как сравнительно новый полупроводник со сверхширокой запрещённой зоной рассматривается как перспективный материал для рентгеновских детекторов и эксплуатации в экстремальных условиях. Тем не менее многие вопросы, связанные с его устойчивостью к радиационным повреждениям и восстановлением после облучения, в настоящее время остаются предметом исследований.

Цель данного обзора — сравнить эти три системы материалов с единой точки зрения, выявив их текущие возможности, а также наиболее перспективные области применения. Добавлены раздел сравнительного анализа и раздел перспектив для определения ключевых направлений будущих исследований, особенно в области стандартизированного бенчмаркинга, оптимизации устройств с учётом дефектов, а также создания более надёжных детекторов для ядерной энергетики и эксплуатации в жёстких условиях.

Ключевые слова: 4H-SiC; GaN; β -Ga₂O₃; широкозонные полупроводники; сверхширокозонные полупроводники.

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