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Journal:	*IEEE Transactions on Nuclear Science*
Manuscript ID	TNS-00676-2021.R1
Manuscript Type:	ANIMMA 2021
Date Submitted by the Author:	n/a

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Standard Key Words:	Detector technology, Diodes, Neutron detectors, Neutron spectroscopy, Nuclear power instrumentation, Radiation detectors, Semiconductor detectors, Silicon carbide devices, Solid state detectors

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Silicon Carbide Neutron Detectors for Harsh Nuclear Environments: A Review of the State of the Art

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***Abstract*— Silicon carbide (SiC) semiconductor is an ideal material for solid-state nuclear radiation detectors to be used in high-temperature, high-radiation environments. Such harsh environments are typically encountered in nuclear reactor measurement locations as well as high-level radioactive waste and/or "hot" dismantling-decommissioning operations. In the present fleet of commercial nuclear reactors, temperatures in excess of 300 °C are often encountered, and temperatures up to 800 °C are anticipated in advanced reactor designs. The wide bandgap for SiC (3.27 eV) compared to more widely used semiconductors such as silicon (1.12 eV at room temperature) has allowed low-noise measurements to be carried out at temperatures up to 700 °C. The concentration of thermally induced charge carriers in SiC at 700 °C is about four orders of magnitude less than that of silicon at room temperature. Furthermore, SiC radiation detectors have been demonstrated to be much more resistant to the effects of radiation-induced damage than more conventional semiconductors such as silicon, germanium, or cadmium zinc telluride (CZT), and have been demonstrated to be operational after extremely high gamma-ray, neutron, and charged-particle doses. The purpose of the present review is to provide an updated state of the art for SiC neutron detectors and to explore their applications in harsh high-temperature, high-radiation nuclear reactor applications. Conclusions related to the current state-of-the-art of SiC neutron detectors will be presented, and specific ideal applications will be discussed.**

***Index Terms*— Neutron detectors, silicon carbide, SiC, semiconductor, radiation damage**

I. Introduction

SILICON Carbide (SiC) semiconductor neutron detectors have many advantages for measurements in harsh high-temperature, high-radiation environments. The material properties of SiC, particularly the 4H polytype [1], make operation in these environments more feasible than for other conventional semiconductors such as Si, Ge, and CZT (Cadmium Zinc Telluride). The 3.27-eV bandgap for 4H SiC enables low-noise measurements at room temperature and temperatures up to at least 700 °C. SiC has also been shown to be resistant to the cumulative effects of gamma, neutron, and charged-particle irradiation. Other factors that are advantageous for SiC include:

- high thermal conductivity
- a maximum breakdown field that is eight times that of silicon allowing higher biases to be applied resulting in higher drift velocities and more efficient charge collection
- a high saturated drift velocity (nearly twice that of silicon) leading to low charge trapping

The use of SiC as a radiation detector material was reviewed by Nava, *et al.* in 2008 [1], Strokan, *et al.* in 2009 [2] and Ruddy in 2013 [3]. Designs and properties of SiC neutron detectors were reviewed by Franceschini and Ruddy in 2011 [4]. The purpose of the present review is to provide an updated state of the art for SiC neutron detectors and to explore their applications in harsh high-temperature, high-radiation nuclear reactor applications.

II. The History of Silicon Carbide Radiation Detector Development

SiC radiation detectors were first demonstrated more than sixty years ago. Initial results were first reported in 1957 [5] and summarized by Babcock and Chang in 1963 [6]. In their groundbreaking work, they demonstrated detection of alpha particles with SiC diodes at temperatures up to 700 °C using diodes produced by aluminum diffusion into SiC crystals grown by sublimation. Follow-on measurements by Ferber and Hamilton [7] used miniature neutron detectors formed by juxtaposing a ^{235}U layer near the sensitive volume of a SiC diode. They demonstrated a linear response to reactor power in the 10^7 to 10^{11} cm^{-2}-sec^{-1} neutron fluence-rate range and performed axial flux maps of a reactor at a fluence rate of 10^9 cm^{-2}-sec^{-1}. Good agreement was found with the results of gold-foil neutron activation dosimetry. The authors also reported that good alpha-particle spectrometry results were obtained with a SiC diode that had been exposed to a thermal neutron fluence of 6 x 10^{15} cm^{-2}.

Development of SiC radiation detectors was also carried out in the Soviet Union by Tikhomirova and co-workers using beryllium-doped 6H SiC. They measured an energy resolution

This paper was submitted for review on September 30, 2021.
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of 8% Full Width at Half Maximum (FWHM) for 4.5-MeV alpha particles. [8,9] Although they observed no degradation of the performance of a neutron detector using a ^{235}U convertor foil up to a thermal-neutron fluence of 5 x 10^{13} cm^{-2} , the detector performance decreased substantially at higher fluences.[10] The authors attributed this effect to neutron damage, but it is likely [4] that their diode performance was determined more by the effects of fission-fragment irradiation (approximately 7 x 10^{8} cm^{-2} fission fragments at a thermal-neutron fluence of 10^{13} cm^{-2}).

Further progress in SiC detector development was hindered by the lack of high-quality crystalline materials and techniques for applying electrical contacts. In the 1990's considerable progress was achieved in reducing SiC crystal defects such as dislocations, micropipes, *etc.*, introduced during the crystal growing process. Also, advanced epitaxial layer-growth technologies enabled the production of much higher quality SiC layers leading to a renewed interest in SiC as a detector material in 1995. The first SiC detectors based on high-quality SiC epitaxy were reported in 1998 by Ruddy, *et al.* [11]. Detectors based on both Schottky diode and p-n junction designs were demonstrated. The authors investigated temperature effects on the performance of the 4H-SiC radiation detectors and measured response to ^{238}Pu α-particles at several temperatures in the 22-89°C range. It was reported that no significant change of detector response was observed up to 89°C at a reverse bias of -20V. In follow-on work by Seshadri, *et al.* [12], a gradual degradation of charge collection efficiency of 4H-SiC Schottky diodes was observed above a thermal-neutron fluence of 5.7×10^{16} cm^{-2} (1.68×10^{16} cm^{-2}, E > 1 MeV) due to neutron-induced defects. It was noted that the observed degradation does not affect the counting characteristics but can limit the possibility of self-biased operation under high neutron fluences. Nevertheless, it was remarked that no significant degradation in the energy resolution was observed. Moreover, these detectors showed well resolved gamma-ray and alpha-particle signals. The obtained results demonstrated that 4H-SiC is a very promising material for applications in high radiation environments.

These initial results using epitaxial SiC diodes were confirmed by Nava, *et al.*,[13] who demonstrated ^{241}Am alpha particle detection with 4H SiC Schottky diodes and showed that charge collection efficiency increased linearly with the square root of the applied reverse bias.

Widespread interest in SiC radiation detectors ensued, and the initial results for alpha particles were rapidly followed by demonstration of detection of X-rays [14], minimum ionizing particles [15] and neutrons [16] using devices based on high-quality SiC epitaxial layers.

More recently, measurements for alpha, X-ray, and neutron detection with SiC detectors have produced results that are comparable to those that are attainable with silicon detectors. [17-23] For example, Mandal, Kleppinger and Chaudhuri [23] have obtained an energy resolution of 15.9 keV (FWHM) for 5486-keV ^{241}Am alpha particles and have calculated an intrinsic energy resolution of 10.5 keV. By comparison, silicon detectors routinely obtain an energy resolution of 10 keV, and the best obtained is 8 keV [24].

Detection of 14-MeV neutrons with SiC detectors [25] yielded reaction-peak energy resolutions that were virtually identical to those obtainable with silicon detectors. The peak widths corresponding to the ground and excited-state branches of the ^{28}Si(n,α)^{25}Mg reaction were indistinguishable for SiC and silicon. Franceschini and Ruddy [26] noted that these widths were likely limited by the effects of reaction kinematics on the production of ionization in the Si and SiC detectors rather than on the characteristics of the detectors themselves. However, an alternative explanation is that the energy spread of the D-T source may have been the primary limiting factor for the observed peak resolutions.

It can be concluded that SiC detectors have evolved to a point that they are capable of being used as an alternative to silicon detectors in harsh environments where the use of the latter is prohibited by temperature and/or radiation damage constraints. Furthermore, SiC detectors can be expected to provide results in these harsh environments that are comparable to those obtainable with silicon detectors operating under ideal conditions.

III. SILICON CARBIDE DETECTOR DESIGNS

By far the most prevalent design for SiC nuclear detectors is the epitaxial layer design shown schematically in Fig. 1. [11-16,23] Although many different polytypes of SiC exist, 4H- SiC is most frequently used for nuclear applications as discussed in detail in reference [1]. The conducting SiC substrate depicted in Fig. 1 typically has a nitrogen dopant concentration of about

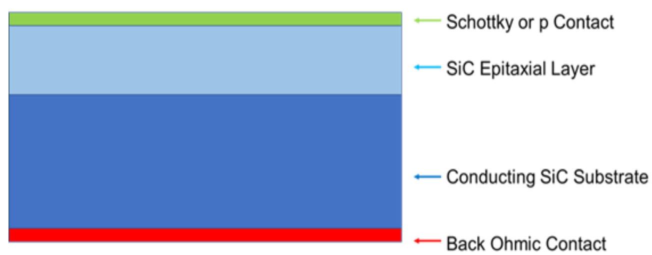

Fig. 1. Schematic representation of a SiC epitaxial diode detector structure.

10^{18} cm^{-3} and a thickness of about 300-350 μm. An n^{-} layer is grown onto the substrate layer using vapor-phase epitaxy. The dopant concentration in the epitaxial layer, which corresponds to the unintentional residual nitrogen concentration, is typically less than about 10^{15} cm^{-3}, and thicknesses ranging from a few μm up to 250 μm have been used. A metallic ohmic contact is applied to the back of the detector using a suitable material such as gold, titanium or nickel. The front contact can be either a Schottky contact using a suitable metal such as nickel or a p^{+} contact formed by diffusing or implanting materials such as aluminum, phosphorus, or boron [11].

If a reverse bias is applied to the SiC diode as depicted in Fig. 2, charge carriers are depleted from the epitaxial layer, and this depleted or intrinsic SiC layer corresponds to the active layer of the detector.

The thickness of the depleted region, measured from the Schottky contact into the epitaxial layer, increases with reverse bias, V, according to the following approximation

$$d \simeq \left[\frac{2\varepsilon V}{eN}\right]^{1/2} \quad (1)$$

where ε is the electrical permittivity for SiC, *e* is the electron charge and N is the effective doping concentration.

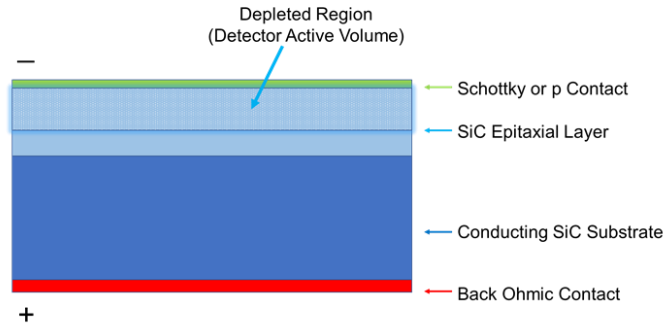

Fig. 2 Application of a reverse bias forms a depletion region in the epitaxial layer which corresponds to the active volume of the detector

It can be seen that the depletion thickness is directly proportional to the square root of the applied voltage and inversely proportional to the square root of the dopant concentration. The thickness of the depleted region for a typical diode is illustrated in Fig. 3. To achieve large active volumes

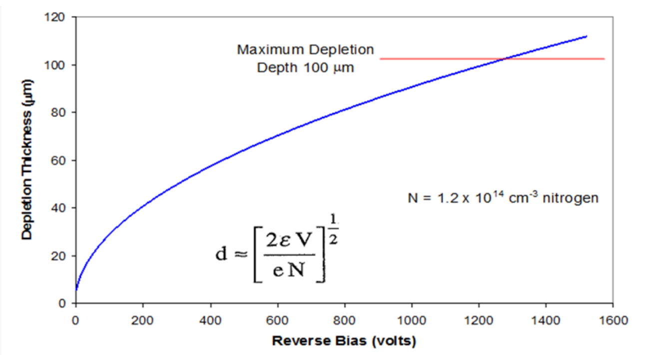

Fig. 3. Depletion depth as a function of applied reverse bias for a 100-µm thick epitaxial layer with a nitrogen concentration of 1.2 x 10^{14} cm^{-3}. The maximum depletion depth (horizontal red line) is the thickness of the epitaxial layer. A reverse bias of 1200 v is required for full depletion. If the reverse bias is limited to 1000 v, a 90-µm depletion depth results.

with thick epitaxial layers, one must have low nitrogen concentrations and/or apply high bias voltages. In practice, one might be constrained to voltages less than 1000 V (to protect the counting chain electronics from voltage discharges). Therefore, thick epitaxial layers with the lowest possible dopant concentrations are desirable. As discussed in reference [3], state-of-the-art SiC epitaxy is limited to nitrogen concentrations of about 10^{13} cm^{-3} , but a goal of 10^{12} cm^{-3} is reasonable [27].

IV. NEUTRON RESPONSE MEASUREMENTS

Neutrons have no electrical charge and are not capable of producing ionization directly in a detector. Therefore, as with all neutron detectors, SiC neutron detectors require a nuclear reaction to form reaction products that are capable of producing ionization within the detector active volume. For thermal-neutron detection, the following high cross-section nuclear reactions have proven useful: [4,28]

^{10}B(n,α)^{7}Li	3840 barns
^{6}Li(n,α)^{3}H	940 barns
^{3}He(n,p)^{3}H	5330 barns
^{235}U(n,f) fission products	585 barns

Compounds containing ^{10}B, ^{6}Li and ^{235}U have been used most frequently for thermal-neutron detection with SiC detectors, because solid-state compounds of these materials are readily available and can be configured to allow the energetic charged-particle reaction products to enter the detector active volume. [4,5-7,10,12,16] In practice, the thermal-neutron convertor material can be in the form of a thin layer juxtaposed near the active volume or can be incorporated into the detector by ion implantation [29] or diffusion [30].

Kandlakunta, *et al.*[31] have investigated the use of Nitrogen as a thermal neutron convertor using the ^{14}N(n,p)^{14}C reaction, which produces 584.0-keV protons. Although a clear response to protons was not demonstrated, Monte-Carlo response modelling of the response spectra of a SiC detector to neutrons in near-core reactor locations showed good agreement and correlated well with reactor power.

Fast neutrons can be detected by ionization produced by ions resulting from nuclear reactions with silicon or carbon atoms in or near to the SiC active volume of the detector. A partial list of reactions is shown in Table I. [4] Other more complex

TABLE I
FAST-NEUTRON INDUCED REACTIONS IN SILICON CARBIDE

Reaction	Threshold Energy (MeV)
^{12}C(n,n')^{12}C (elastic scattering)	0
^{28}Si(n,n')^{28}Si (elastic scattering)	0
^{12}C(n,n')^{12}C (first excited state)	4.809
^{28}Si(n,n')^{28}Si (first excited state)	1.843
^{12}C(n,α)^{9}Be	6.180
^{28}Si(n,α)^{25}Mg	2.749
^{12}C(n,p)^{12}B	13.643
^{28}Si(n,p)	3.999

reactions, such as (n,2n), (n,pn), (n,nα), *etc.* are also possible as well as reactions with less abundant isotopes of carbon and silicon. For fast-neutron spectra derived from energy moderation of fission neutrons, the response of a SiC detector will be dominated by the detection of energetic ^{12}C and ^{28}Si ions from (n,n') elastic and inelastic scattering reactions, because the average energy of fission neutrons is ~2 MeV with most of the neutrons having energies less than 6 MeV. Those threshold reactions that are energetically possible will add to the pulse-height continuum, because the incident neutron spectrum is a distribution of energies leading to a distribution of recoil-ion energies. A comparison of the thermal-neutron and fast-neutron responses for a SiC detector is shown in Fig. 4, which has been reproduced from Reference 32. Both spectra were taken for the same period of time at a reactor power of 500 watts.

When the ^{6}LiF converter foil is present, the detector response is dominated by the ^{4}He and ^{3}H ions produced by thermal-neutron reactions. Although events from fast-neutron induced reactions are present in the spectrum, they are obscured by the thermal neutron-induced events, which are much more abundant.

The fast-neutron spectrum (no converter foil) shown in Fig. 4 is a continuum dominated by elastic and inelastic neutron scattering reactions with carbon and silicon atoms in the SiC detector as discussed previously. The events below channel 300 are due primarily to gamma-ray induced secondary-electrons.

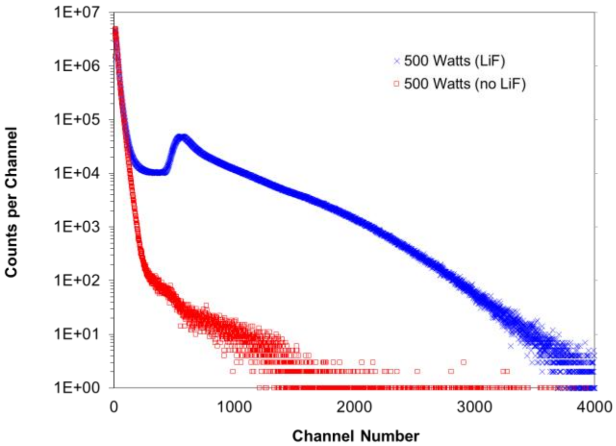

Fig. 4. Comparison of the neutron response of a 500-µm diameter x 3-µm SiC Schottky diode to reactor fission neutrons with and without a 24.2-µm ^{6}LiF convertor foil. With the ^{6}LiF foil present, the detector response is primarily to thermal neutrons When the ^{6}LiF foil is absent, the detector responds primarily to fast neutrons. (Figure reproduced from Reference 32).

The ranges of these electrons in SiC are large compared to the dimensions of the detector active volume resulting in only a fraction of the energy from each being detected. Although only a featureless low-energy continuum results, the detector response to gamma rays has been shown to be linear. [33-35] The fast-neutron response is complex and results in no peaks in the spectrum. Nevertheless, incident neutron energy information is present as shown by the data in Fig 5. [25].

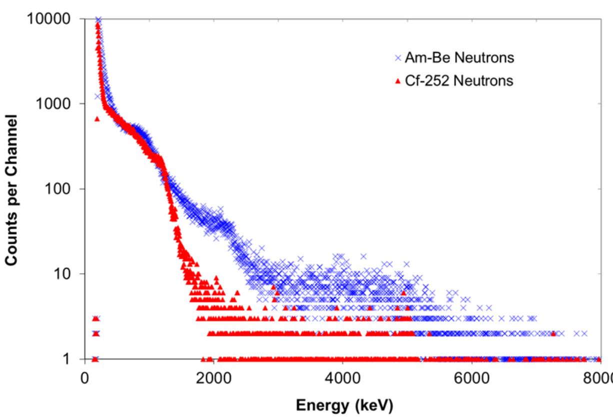

Fig. 5. Comparison of the responses of a SiC detector to fission neutrons from ^{252}Cf and neutrons from an ^{241}Am-beryllium source. (Adapted from reference 25)

The average energy of neutrons from fission of ^{252}Cf is 2.15 MeV, whereas the ^{241}Am-Be source produces a much higher average energy of 4.5 MeV. The ^{241}Am-Be detector response continuum is clearly shifted to higher pulse heights compared to the ^{252}Cf response spectrum. This effect is also apparent in the data of Fig. 6, where the responses to neutrons from ^{252}Cf spontaneous fission decay and neutron-induced ^{235}U fission are compared. [36] The average neutron energy from ^{252}Cf spontaneous fission decay is 2.15 MeV and the average energy from thermal-neutron induced fission of ^{235}U is 2.5 MeV, and the latter spectrum is shifted to higher energies compared to the former.

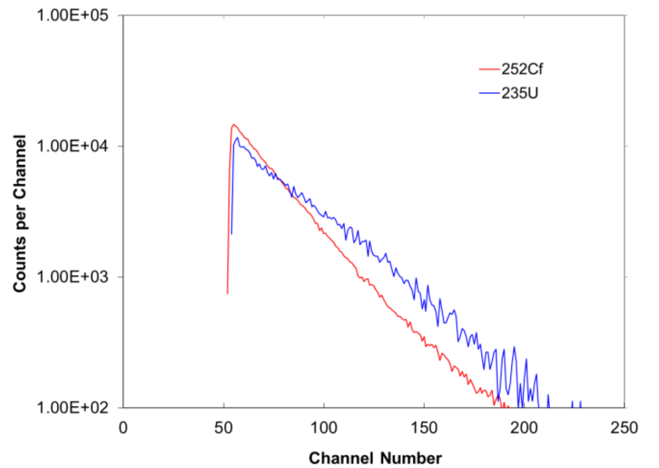

Fig. 6. Comparison of the response spectra of a SiC detector to neutron-induced fission neutrons from ^{235}U and ^{252}Cf spontaneous fission neutrons. (Adapted from Reference 36)

In order to extract neutron-spectrum information from the pulse-height response, a complex unfolding procedure using a combination of neutron transport and recoil range calculations is required. The calculations of Reference 26 for the monoenergetic 14-MeV neutron response spectrum of a SiC detector are a promising start towards this goal.

In the case of monoenergetic neutrons impinging on a SiC detector, peaks will be present for those reactions that result only in charged-particle products. For example, the $^{12}C(n,\alpha)$ reaction (see Table I) results only in ^{4}He and ^{9}Be ions which share the energy of the incident neutron plus the reaction energy. Therefore, a peak will be observed corresponding to ionization resulting from a total energy of 8298.8 keV being deposited in the detector active volume. The response spectrum for a SiC detector exposed to 14.1 MeV neutrons from a Deuterium-Tritium (DT) neutron generator is shown in Fig. 7, which has been reproduced from Reference 25.

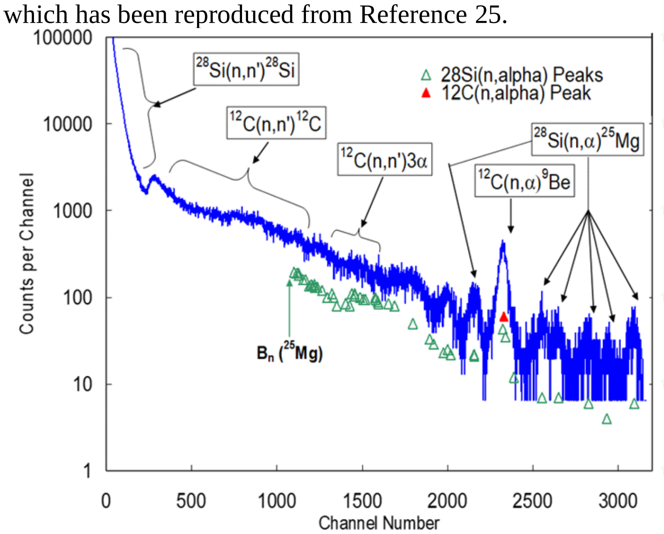

Fig. 7. Response spectrum for a 6 mm^{2} x 100 µm SiC detector exposed to 14.1 MeV DT neutrons. (Reproduced from Reference 25)

In addition to the prominent peak from the $^{12}C(n,\alpha)^{9}Be$ reaction, a family of peaks corresponding to the $^{28}Si(n,\alpha)^{25}Mg$ reaction is also present. The highest-energy peak corresponds to the production of the ground state of ^{25}Mg with the deposition of a total energy of 11,346 keV in the SiC detector active volume. The other peaks in this set correspond to excited states of ^{25}Mg where less energy is deposited in the detector. The difference in energy corresponds to gamma rays produced when these excited states of ^{25}Mg decay to the ground state. As the energies of these excited states increases, the energy spacing between them decreases, and the peaks are not resolved above about the tenth excited state. The higher energy states will produce a continuum of events up to the ^{25}Mg neutron binding energy, B_n, above which the ^{28}Si(n,n'α)^{24}Mg reaction will dominate. Since the energy of the neutron produced in this reaction is not fixed, no peaks will result from this reaction.

Notably absent are peaks corresponding to the ^{28}Si(n,p) and ^{12}C(n,p) reactions. The protons produced in these reactions have energies that results in ranges in SiC that are much larger than the thickness of the detector active volume. Therefore, only a varying fraction of the energy from these reactions is deposited in the active volume, and the peaks are obscured by this finite detector volume effect [25,26].

Continua from elastic and inelastic neutron scattering as well as more complex reactions such as ^{12}C(n,n')3α are also present. No single peak is observed for these reactions, because the energy of the reaction product neutron is not fixed.

The neutron responses for SiC detectors have been shown to be linear for thermal [16], epithermal [33,34], fast [32] and 14-MeV neutrons [37]. Furthermore, the neutron response is separable on the basis of pulse height from the gross gamma-ray response [12,16,33], and gamma-ray response has also been shown to be linear [33-35].

V. Neutron-Response Measurements at High Temperatures

Some applications such as fusion-reactor technologies require stable measurement methods to detect neutrons and charged particles under extreme conditions such as high temperatures and high magnetic fields. To maintain the fusion process, it is mandatory to measure simultaneously the neutron flux and the tritium breeding ratio.

Specific fast neutron detectors, based on 4H-SiC pn diodes, were developed in the framework of the European I_SMART project [38]. The characteristics of these detectors were measured at room temperature and compared with a single-crystal chemical vapor deposited (sCVD) diamond-based detector (purchased from CIVIDEC Instrumentation Company). Measurements were carried out at the DT neutron generator at Technical University of Dresden (TUD). The detectors were positioned at 13 cm away from the tritium target at an angle of 90° with respect to the deuteron beam. The neutron fluence rate at this point was calculated to be about 9.4×10^{6} cm^{-2}-s^{-1} with a neutron energy of 14.12 MeV.

Fig. 8 shows that both detectors produce pulse-height spectra with the well-resolved peak due to the ^{12}C(n,α)^{9}Be reaction. The count rate of the diamond-based detector is higher than that of the SiC-based detector as a consequence of the higher thickness of the diamond active detection volume. The energy resolution of this peak is slightly better for the 4H-SiC-based detector (260

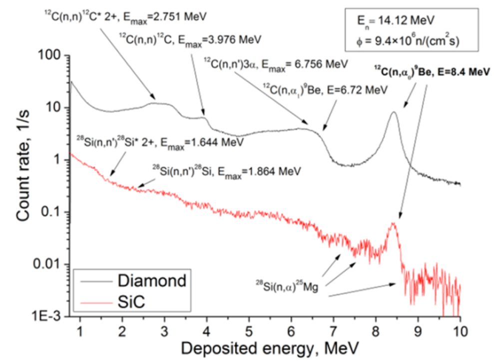

Fig. 8. Comparison of the responses of SiC-based and CVD diamond-based detectors to 14.12 MeV neutrons. (Figure reproduced from Reference [38].)

keV at FWHM which corresponds to 3.09%), with respect to 303 keV (3.6%) for the diamond detector. An important phenomenon is the improvement of the energy resolution with increased neutron flux for the SiC detector, in complete opposition to the behavior of diamond [38]. The cause of this behavior is not understood at this time.

Several prototypes were also tested in industrial conditions at the fast neutron generator at Schlumberger (Clamart, France), at room temperature and at 106 ° C [39]. The spectra show good stability, preserving features over the whole temperature range. Prototypes with gold metallic contacts were then tested up to 500 °C at the DT neutron generator at the TUD [40]. In the recorded spectra, the different signal structures arising from high-energy deep inelastic reactions can be distinguished, independently of the temperature (see Fig. 9). The most prominent orientation point in the spectrum is the full energy peak of the ^{12}C(n,α)^{9}Be reaction, which can be clearly distinguished at all the applied temperatures.

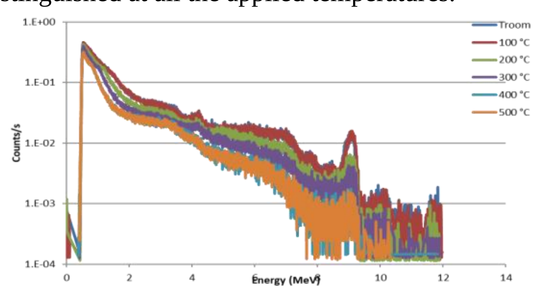

Fig. 9. Energy spectra recorded during irradiation tests of SiC-based detectors with 14 MeV neutrons at different ambient temperatures. (Figure reproduced from reference 40).

Abubakar, *et al.* [41] reported stability of the SiC-based alpha detector signal at 500 K (227 °C) over a period of 18 hours.

Wang, *et al.*[42] performed measurements of the response of a SiC detector to a weak ^{241}Am alpha-particle source in the presence of an intense ^{60}Co gamma-ray background and observed some degradation of the alpha energy resolution due to pulse pile up and secondary trapping effects. At temperatures up to 500 °C, only slightly degraded energy resolution was observed. Stable SiC spectral responses were observed during ~2-hour gamma-ray, neutron-beam and near-core irradiations.

No temperature-induced polarization effect has been observed to date with epitaxial Silicon Carbide, in contrast to the case of diamond where this effect appears above 600 K (327 °C) [43].

VI. Radiation Damage Effects in Silicon Carbide Detectors

Whereas conventional neutron detectors such as fission chambers and self-powered neutron detectors exhibit excellent resistance to the cumulative damaging effects of radiation, some monitoring applications are potentially better suited to semiconductor detectors. Common semiconductor detectors based on silicon or germanium are not only limited to low-temperature operation, because of low band gaps, but also have low service lifetimes due to radiation damage effects. Therefore, these detectors have been of little use in harsh nuclear environments where large doses of gamma rays, neutrons and charged particles must be tolerated.

For example, silicon detectors show increasing leakage current when exposed to radiation due to the formation of defects that correspond to charge-donor levels in the band gap. Charge-trapping sites are also produced, but the increased leakage current is the primary radiation-damage limitation for the use of silicon detectors and is an indirect consequence of the low band gap for silicon.

On the other hand, wide band-gap semiconductor detectors such as SiC are limited more by the accumulation of charge-trapping sites. Increased leakage current due to the formation of charge-donor states is less due to the larger band gap.

SiC has been shown to be highly resistant to the effects of radiation damage. The effects of large gamma-ray doses on the performance of SiC detectors have been investigated by several groups. Kang, *et al.* [44] showed that irradiating 6H SiC diodes with a dose of 120 kGy of ^{60}Co gamma rays leads to a leakage-current decrease. Metzger, *et al.* [45], observed no change in the ^{60}Co gamma-ray detection efficiency of 6H SiC photodiodes after a 1.080 MGy dose of ^{60}Co gamma rays, and Kinoshita, *et al.*[46], observed no change in the 100% charge-collection efficiency of 6H SiC p-n diodes after a ^{60}Co gamma-ray dose of 2.5 MGy. Ruddy and Seidel [47,48] irradiated 4H SiC Schottky diodes to a cumulative ^{137}Cs gamma-ray dose of 22.7 MGy. ^{137}Cs gamma rays were used to simulate the radiation environment of spent-fuel assembly five years after discharge from a nuclear power reactor. Photographs of the 6-mm^2 x 100-µm diode before and after the irradiation are shown in Fig. 10.

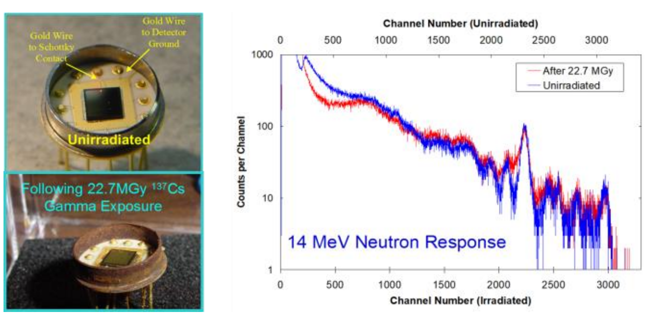

Fig. 10. Photographs of a 6-mm^2 x 100-µm SiC Schottky diode before (top) and after (bottom) exposure to a cumulative ^{137}Cs gamma-ray dose of 22.7 MGy and comparison of the corresponding neutron responses (Figures adapted from reference 48)

The irradiation was carried out in a dry-Nitrogen environment to minimize corrosion and other chemical/radiolytical effects on the detector. Although the physical damage effects of the gamma-ray exposure on the detector are apparent from the photos, the irradiated detector was found to perform well as a detector for fast ^{252}Cf fission neutrons and for 14-Mev D-T neutrons [48]. The 14-MeV neutron response spectrum for the irradiated detector is compared to an identical unirradiated detector in Fig. 10. The observed difference between the before- and after-irradiation spectra are minor. Although a higher operating voltage was required for the irradiated-detector spectrum, the ^{12}C(n,α)^{9}Be and ^{28}Si(n,α)^{25}Mg reaction peaks are apparent in both spectra.

Whereas the radiation effects of gamma rays on the response and operational lifetimes of SiC detectors are minor, the effects of charged particle and fast neutron damage are more formidable. For SiC detectors exposed in neutron environments, the radiation effects of fast neutrons as well as the charged particles produced by neutron convertor reactions (*e.g.*, ^{6}Li[n,α]^{3}H), ^{10}B[n,α]^{7}Li, ^{235}U[n,f]) are both primary concerns. As noted previously in Section 2.0 of this manuscript, Tikhomirova, *et al.* [10] noted degradation of Beryllium-doped 6H SiC detectors at thermal-neutron fluences greater than 10^{13} cm^{-2} for devices using a uranium convertor foil. However, the degradation was more likely due to the fission product ions from the convertor foil than from the neutrons impinging on the detector.

An early neutron-damage study carried out by Ferber and Hamilton [7] showed that good alpha-particle spectrometry results were obtained with a SiC diode equipped with a ^{235}U convertor foil that had been exposed to a thermal neutron fluence of 6 x 10^{15} cm^{-2}. However, the fast-neutron fluence was not reported, and any radiation damage to the detector would have been caused by fast neutrons and fission fragments.

Dulloo, *et al.*, [16, 49] showed that the thermal-neutron response of a SiC Schottky diode with a ^{6}LiF convertor foil was indistinguishable from that of an unirradiated detector after a fast-neutron (E >1 MeV) fluence of 1.3 x 10^{16} cm^{-2}.

Lo Giudice , *et al.*, [50] irradiated large area 4H-SiC Schottky diodes equipped with a ^{6}LiF convertors with epithermal neutrons and observed less than 0.3% decrease in the count rate after a neutron fluence of 10^{13} cm^{-2}. They attributed this minor decrease to alpha-particle damage from the ^{6}Li(n,α)^{3}H convertor layer. The more energetic ^{3}H ions would be expected to produce less localized damage.

Afanasyev, *et al.*, [51] examined the photosensitivity of SiC UV photodiodes and observed no change in performance after a fast-neutron fluence of 5 x 10^{12} cm^{-2}, but observed degradation of I-V-characteristics, reduction of carrier lifetimes and, as a result, reduction of the photosensitivity of their devices at higher fluences up to 1 x 10^{14} cm^{-2}. They attributed the performance changes to the creation of deep recombination centers, which will interfere with charge collection.

Nava, *et al.*, [52] performed a comprehensive study of the detection properties of 4H SiC Schottky diodes irradiated with 1 MeV neutron fluences up to 8 x 10^{15} cm^{-2}. They observed only minor (~20%) losses in charge-collection efficiency at fluences up to 10^{15} cm^{-2} , which they attribute to the detector behaving more as "intrinsic" SiC material due to compensation of the dopant atoms by traps. At fluences higher than 10^{15} cm^{-2} the charge-collection losses increase monotonically to ~80% loss at 8 x 10^{15} cm^{-2}. They attributed the degradation to the production of two types of deep-level traps, which correspond to neutron-induced carbon and silicon vacancies.

An earlier study by Seshadri, *et al.*, [12] reached a similar conclusion. They found that the charge collection efficiency for ^{238}Pu alpha particles decreased systematically, and that self-biased operation was not possible following an accumulated fast-neutron (E > 1 MeV) fluence of 5.7 x 10^{16} cm^{-2}. The reduction in charge-collection efficiency was systematic and corresponded to a carrier removal rate of 9.7±0.7 cm^{-1}, which the authors attributed to the introduction of deep-level traps by fast-neutron interactions.

A later study by Wu, *et al.* [53] found that the charge collection efficiency for self-biased 4H SiC Schottky diodes reduced to 1.3% of the unirradiated value after irradiation with a fast-neutron fluence of 8.26 x 10^{14} cm^{-2}.

Liu, *et al.* [54] compared the performance of Si and SiC neutron detectors following irradiations with 14.86-MeV neutrons from a D-T accelerator. They observed more than four orders of magnitude increase in the Si detector dark current and a severe reduction (over 95%) in the ^{239}Pu α peak centroid position after a D-T neutron fluence of 1.65 x 10^{13} cm^{-2}. The SiC neutron detector showed nearly no degradation up to a higher fluence of 3.82 x 10^{13} cm^{-2}.

Systematic investigations were made by Ruddy, *et al.*, [55] of the effects on detector performance of both fast (E > 1 MeV) neutrons and energetic ^{3}H and ^{4}He ions from reactions in a ^{6}LiF convertor layer. SiC pn and Schottky diodes with 200 µm diameters and 8- µm epitaxial layers with a nitrogen dopant concentration 1 x 10^{15} cm^{-3} as described in Reference [11] were irradiated in three configurations. Detectors with a juxtaposed ^{6}LiF convertor layer, with a 6- µm aluminum foil between the detector and the ^{6}Lif layer, and with no convertor layer were irradiated to evaluate the effects of neutrons plus ^{3}H plus ^{4}He, neutrons plus ^{3}H, and neutrons only, respectively. Following irradiation, the detectors were tested with a ^{238}Pu alpha-particle source as described in Reference [11] in order to evaluate charge-collection efficiency as a function of accumulated neutron and charged-particle fluence. The pulse-height response of the three detector configurations after a thermal-neutron fluence of 3.9 x 10^{16} cm^{-2} is shown in Fig. 11.

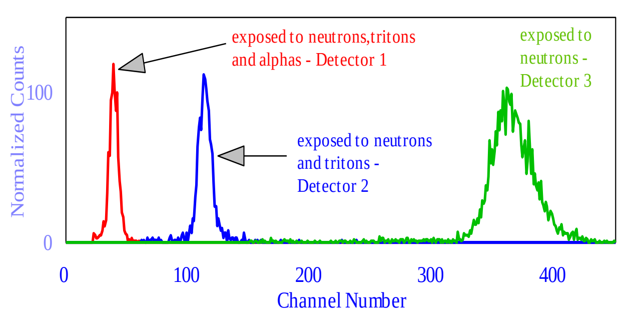

Fig. 11. Comparison of the ^{238}Pu pulse-height response of three detector configurations following irradiation. (Figure reproduced from Reference 55)

In all three cases, the pulse height is reduced following irradiation. As expected, the largest shift is obtained for the case where the detector is exposed to neutrons plus ^{3}H and ^{4}He, the lowest shift is for neutrons only, and an intermediate shift is obtained for neutrons plus ^{3}H. The observed pulse-heights decreased with increasing neutron fluence for all three configurations. For detectors exposed to neutrons only, a rapid decrease was observed up to a fast-neutron fluence of about 10^{14} cm^{-2}, followed by a much more gradual decrease at higher fluences. This was attributed [55] to the introduction of charge-trapping sites corresponding to a carrier removal rate of 9.7 cm^{-1} as measured in Reference [12] until the nitrogen doping concentration of 10^{15} cm^{-3} was fully compensated. After full compensation, the SiC behaves as intrinsic material [55].

Based on a simple first-order model of charge-carrier loss as a function of charge-trap density [56], it was shown [55] that the observed pulse height should be proportional to the reciprocal of the accumulated fast-neutron fluence. Such a plot for the observed pulse heights for an irradiated SiC detector with no convertor layer (neutron damage only) is shown in Fig. 12.

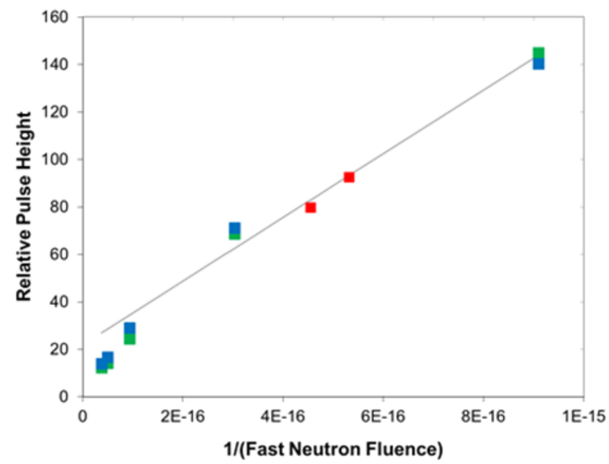

Fig. 12 ^{238}Pu pulse heights for SiC diodes exposed to fast neutrons. Pulse height is plotted as a function of reciprocal fast-neutron fluence. (Figure reproduced from Reference [55])

The fast-neutron fluence corresponding to the lowest observed pulse height in Fig. 12 is 1.1 x 10^{17} n cm^{-2}. The ambient reactor temperature in the irradiation position was 45 °C. An approximate linear relationship between pulse height and reciprocal fast-neutron fluence is observed over the entire range of the measurements, consistent with the predictions [12,55,56] of the simple first-order model which assumes that loss of charge carriers is directly proportional to the density of charge traps produced in the SiC.

A similar plot for the cases where a ^{6}LiF foil with (n + ^{3}H) and without (n + ^{3}H + He^{4}) an aluminum absorber adjacent to the SiC diodes during irradiation is shown in Fig. 13. Rather

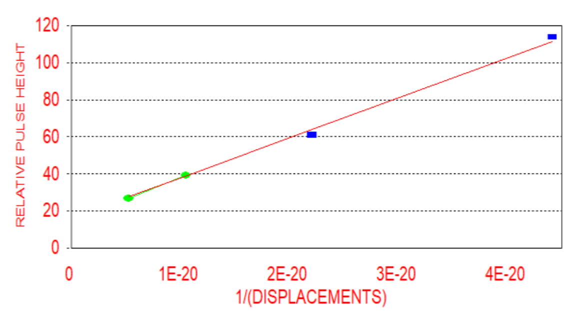

Fig. 13 ^{238}Pu pulse heights for SiC diodes exposed to fast neutrons and neutron reaction-product ions. Pulse height is plotted as a function of reciprocal calculated displacements. The ovals correspond to neutron plus triton plus alpha-particle exposures and the squares correspond to neutron plus triton exposures (Figure reproduced from Reference [55]) than neutron fluence, calculated displacements were used to account for the relative damage produced by neutrons and tritons. Again, a straight-line relationship is observed over the entire range of the irradiations which were carried out at 45 °C.

In all cases, although the alpha-response peak centroid was shifted, the detector count rate for alpha-induced events was unaffected for the exposure ranges studied, and the signals for gamma and alpha radiation were still separable. [55]

It was observed by McLean, *et al.* [57] that the effects of neutron irradiation on 6H SiC JFETs were less severe if the irradiation occurs at higher temperatures. They observed a change in the carrier removal rate from 3.5 cm^{-1} at room temperature to 4.75 cm^{-1} at 300 °C. Scozzie, *et al.* [58] observed no onset of JFET performance changes up to a neutron fluence of 1 x 10^{15} cm^{-2} at room temperature. Irradiation at 300 °C extended the onset of changes to 5 x 10^{15} cm^{-2}. It was concluded [58] that elevated temperature irradiation mitigates the effects of the irradiation-induced damage.

This potential effect was investigated by Ruddy, *et al*, [55] who performed further irradiations at 230 °C. The data for neutrons-only irradiations at 230 °C and 45 °C are compared in Fig. 14. The results at both temperatures are fit well by a

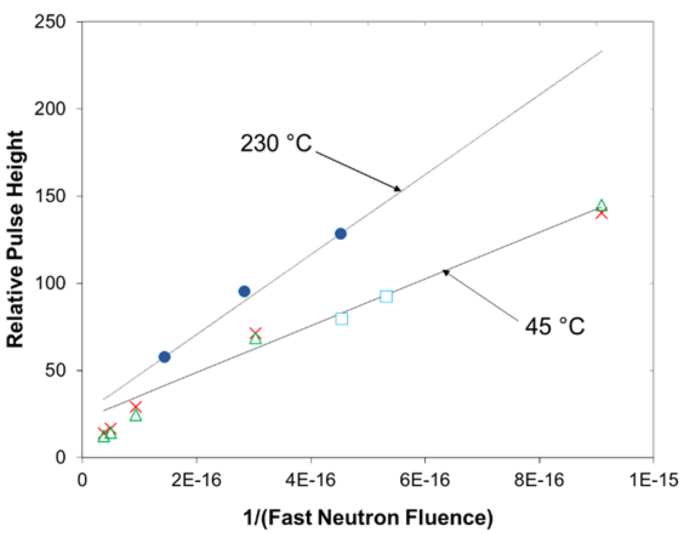

Fig. 14. Effect of elevated temperature during neutron irradiation on the observed pulse heights from a ^{238}Pu alpha test source. Pulse height is plotted as a function of reciprocal fast neutron fluence. The symbols refer to different irradiated SiC detectors. (Figure adapted from Reference 55)

straight line, consistent with the predictions [12,55,56] of a simple first-order model which assumes that loss of charge carriers is directly proportional to the density of charge traps produced in the SiC active volume by fast neutrons. A similar relationship was observed for the charged-particle results at 230 °C, where ^{238}Pu pulse height was found to be proportional to the reciprocal of the calculated displacements caused by the fast neutrons, ^{3}H ions and ^{4}He ions

It can be seen from Fig. 14 that the 230 °C irradiations produce significantly higher charge collection than the 45 °C irradiations. It was concluded by the authors [55] that elevated temperature mitigates the effects of the radiation damage on charge collection, but that more data are needed at temperatures of 300 °C and higher. An important implication of these results is that operation in an elevated-temperature environment may significantly *extend* the service lifetime of a SiC neutron detector.

The mechanisms involved in mitigation of radiation damage effects during elevated-temperature irradiations are not clear at present due to the paucity of elevated-temperature data. More data are needed to better understand this phenomenon, which is potentially beneficial for SiC detector applications in harsh environments.

VII. Applications in Harsh Nuclear Environments

Selected potential harsh-environment applications of SiC neutron detectors are discussed in the following sections.

A. Spent Fuel Monitoring

Although monitoring of spent fuel does not involve temperatures significantly above room temperature, extremely harsh gamma-ray environments with high gamma-ray to neutron ratios are generally encountered. During reactor irradiation, nuclear fuel acquires a neutron specific activity, primarily due to the buildup of higher actinides by successive neutron reactions originating with the ^{238}U component of the fuel. [33-35] These actinides produce neutrons through spontaneous fission of isotopes such as ^{240}Pu, ^{242}Cm and ^{244}Cm. During the first operating cycle, ^{240}Pu will dominate, but for a fully burnt fuel assembly several years after discharge, the primary neutron-producing isotope will be 18.1-year ^{244}Cm. In the case of oxide fuels, neutrons are also produced by the alpha-emitters present through $^{18}O(\alpha,n)$ and $^{17}O(\alpha,n)$ reactions. Gamma rays will also be present primarily from the fission-product inventory present in the fuel. For example, a Pressurized Water Reactor (PWR) fuel assembly with a burnup of 25,655 MWd/MTU had a total surface neutron fluence rate of 8000 cm^{-2}-s^{-1} at midplane three years after discharge [59], and typical gamma dose rates in spent-fuel environments are in the 10^{2} -10^{3} Gy/hr range [34-35].

Natsume, *et al.*, [35] tested a SiC neutron detector in a spent fuel pool, and over a 2050-hour (85.4-day) period of continuous monitoring the detector neutron and gamma response did not change or deteriorate. At the detector location, the fluence rates were 180 cm^{-2}-s^{-1} and 11 Gy/hr for fast neutrons and gamma rays, respectively. Both the gamma-ray and neutron count rates, which were separable on the basis of pulse height, were stable to a precision of 1.7% and 2.9% for gamma rays and neutrons, respectively. [35]

The high radiation resistance, stability in elevated and changing temperatures and small size and versatility of SiC detectors make them extremely useful for spent-fuel monitoring applications.

B. Safeguards Monitoring

A related safeguards-monitoring application is long-term monitoring of spent fuel. The axial distribution of the neutron emission rate at the surface of a spent fuel assembly will depend on the burnup history of the assembly as shown in Fig. 15. [59]. The neutron fluence rates calculated from the measured ^{235}U (bare and cadmium covered), ^{238}U, and ^{237}Np fission rates are plotted as a function of axial location on the assembly face. The fast-neutron fluence rates show axial variations which reflect the local fuel burnup history. The thermal- and epithermal-

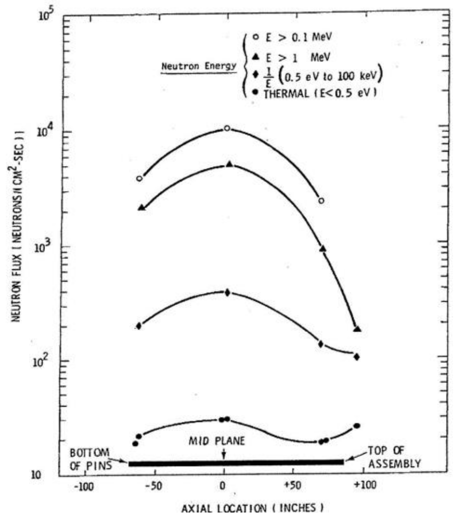

Fig. 15 Axial neutron fluence rate distributions for a typical PWR spent-fuel assembly (Figure reproduced from Reference [59].

neutron fluence rate axial distributions were influenced by room-return (*e.g.*, neutron energy moderation in the walls of the hot cell where the measurements were carried out) and reflect the local environment as well as the characteristics of the fuel assembly resulting in flatter axial distributions. [59]

SiC neutron detectors can be used to monitor thermal and epithermal neutron fluence rates as well as the fast-neutron energy spectrum as a function of axial position either by affixing detectors near the surface of the assembly or inserting a stringer of detectors within an assembly guide tube. SiC neutron detectors can be used for measurements within spent-fuel shipment or storage casks. Deviations from the expected neutron energy spectra or spatial distributions can be used as an indicator of off-normal conditions resulting from, for example:

- diversion of fuel rods – reduced neutron fluence rates will be observed near the missing rod location.
- mechanical or corrosive deterioration of the assembly will perturb the measured distribution of neutron fluence rates.
- water incursion – increased neutron thermalization will be observed due to the moderating effect of the water

It has been demonstrated [55] that after a fast (E>1MeV) fluence of 1.7 x 10^{17} cm^{-2}, SiC neutron detectors are still functional. In a typical spent fuel neutron environment, it would take 5-50 million years to reach this dose. It has also been shown that SiC detectors operate well after a ^{137}Cs dose of 22.7 MGy [48]. If a SiC detector were to be placed adjacent to or within a spent fuel assembly immediately after discharge and left in place indefinitely, this dose would *never* be reached.

Therefore, SiC neutron detectors are capable of continuously monitoring a spent fuel assembly following discharge from the reactor, during transportation and following deposition in a spent fuel repository.

C. Monitoring of Nuclear Fusion Devices

Monitoring of nuclear fusion devices and reactors is required to obtain information on important operational parameters such as fusion power and plasma temperature. In a fusion power reactor, such as the International Thermonuclear Experimental Reactor (ITER) currently under construction in Cadarache, France, the neutron intensity and energy distribution can be used to deduce information on the fusion power and ion temperature [60].

A schematic representation of a Tokamak fusion reactor with tritium-breeding capabilities is shown in Fig. 16.

Fusion is produced in a dense, high-temperature, magnetically confined plasma. The primary energy-producing reaction is

$$^{3}H + {}^{2}H \rightarrow {}^{4}He + n \quad (E_n = 14.1\ MeV),$$

But the following reactions are also taking place:

$$^{2}H + {}^{2}H \rightarrow {}^{3}He + n \quad (E_n = 2.5\ MeV)$$

$$^{2}H + {}^{2}H \rightarrow {}^{3}H + {}^{1}H$$

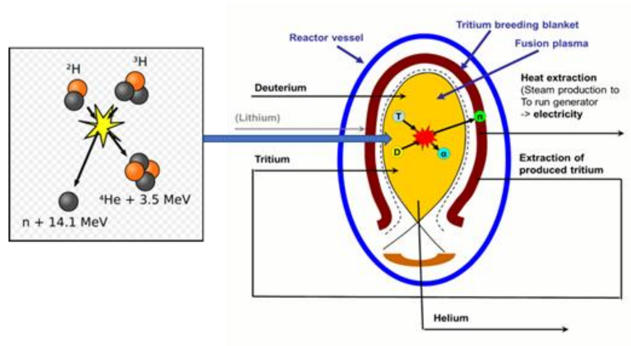

Fig. 16. Schematic representation of a Tokamak nuclear fusion reactor.

as well as other secondary ion reactions. The plasma and its surroundings are an extremely harsh measurement environment with temperatures exceeding 150,000,000 °C. In Test Blanket Modules (TBMs) in the ITER wall, temperatures can reach up to 920 °C in the breeder material, up to 550 °C in the EUROFER structure, and up to 650 °C in the neutron multiplier. Magnetic fields of ~4T are present and measurements must be carried out with extremely limited access/space.

SiC neutron detectors are potentially capable of providing detailed neutron spectra under these conditions as discussed in Sections IV-V. Peaks from $^{12}C(n,\alpha)^{9}Be$ and $^{28}Si(n,\alpha)^{25}Mg$ reactions can provide information on the D-T fusion energy as well its energy width. The reaction peaks can be measured to an energy resolution of 2.2-2.3% FWHM, equal to the energy resolution obtainable with Si detectors [25], which have no prospects for operating in a fusion reactor environment.

SiC detectors have been proposed and are being tested for in-vessel tokamak measurements [61], and promising preliminary results have been obtained.

Concepts are also being developed to demonstrate on-line breeding of tritium to fuel the fusion reaction. TBMs integrated inside the tokamak wall will produce tritium from lithium via the following reactions:

$$^{6}Li + n_{th} \rightarrow {}^{3}H + {}^{4}He \quad (Q = 4.78\ MeV)$$

$$^{7}Li + n \rightarrow {}^{3}H + {}^{4}He + n$$

SiC neutron detectors can be used to monitor the thermal-neutron fluence rate at key locations in and around the TBMs. If a LiF convertor is used, the detector count-rate is a direct measure of the tritium production reaction rate.

Indeed, SiC has been proposed as a candidate detector for TBMs and is undergoing testing. [40]

In addition to neutron measurements, SiC charged-particle detectors can be deployed to obtain information on yields of charged particles (^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He) from fusion and breeder reactions.

D. Monitoring of Test and Research Reactors

Advanced test and research reactors are coming online to address new requirements that can not be met by the current aging fleet. An example is the Jules Horowitz Reactor (JHR), which is currently under construction at CEA Cadarache, France [62]. These reactors will address nuclear materials and fuels irradiation testing needs being generated by advanced commercial nuclear power plant designs that employ innovative high-temperature coolants such as liquid metals and molten salts. Neutron monitoring is required for testing in the high-temperature and high fluence-rate environments typical of reactors such as JHR.

In the framework of the European I_SMART project [63], new 4H-SiC based neutron detectors were developed and tested and have been demonstrated to be able to operate in harsh environments and detect both fast and thermal neutrons. [64-66] Prototypes with various designs were fabricated, some of them optimized for thermal neutron detection via a specific boron converter layer (either deposited on top of the structure or implanted in the anode ohmic contact layer). These detectors have been tested at the MINERVE zero power reactor and in the SCK•CEN BR1 reactor (at fluence rates of the order of 10^9 cm^{-2}-s^{-1}) using prototypes of various sizes, with and without ^{10}B (implanted at room temperature or at 400 °C). These measurements proved the linearity of the detector responses with reactor power. In addition, thermal neutron detection spectra were recorded as a function of bias voltage. Zero bias operation was demonstrated and shown to give the best gamma-ray discrimination consistent with the thin active volume produced by the zero-bias p-n diode potential.

Tests are planned in the Joseph Stefan Institute TRIGA reactor at fluence rates of the order of 10^{12} cm^{-2}-sec^{-1}, leading to high fluence and fluence-rate testing at the 100-MW JHR.

E. Monitoring of Advanced Nuclear Power Reactors

Many of the advanced nuclear power reactors under development utilize extremely high-temperature coolant concepts. See, for example Reference [67]. TERRAPOWER's Natrium Reactor is a sodium-cooled fast reactor with a molten-salt energy storage system. Kairos Power's KP-FHR reactor employs fluoride-salt cooling, and Southern Company's Molten Chloride Reactor also requires molten-salt cooling. High-temperature gas reactor designs, such as X-Energy's XE-100 also involve high operating temperatures. These reactors under development will require neutron monitoring at temperatures up to 850 ° C and will present challenges to the present gas-filled and self-powered neutron detector technology. SiC neutron detectors have been demonstrated at temperatures up to 700 °C and likely can operate at much higher temperatures (4H SiC sublimes at 2857 °C).

SiC neutron detectors have been proposed [68] as an alternative to the gas-filled neutron detector reactor power monitors used in the current fleet of PWRs and Boiling Water Reactors as well as for a proposed advanced PWR design. [69] Among the advantages identified are wider dynamic range, elimination of gamma compensation, and improved reliability of supply. Whereas implementation and qualification of completely new power monitoring systems is extremely difficult in power reactors that are currently in operation, development of advanced water-cooled reactors, such as Holtech International's SMR-160 (an advanced light-water small modular reactor) and Westinghouse's eVinci (a heat pipe-cooled microreactor) as well as the BWXT Advanced High-Temperature Gas-Cooled microreactor [67] will likely require new and innovative neutron detectors for reactor power monitoring instrumentation and control (I&C). Implementation of traditional gas-filled neutron detectors may be cumbersome or even impossible in these new reactor designs. I&C systems based on SiC neutron detectors provide an alternative which can improve the reliability and practicality of these small and micro reactors.

VIII. Conclusions and Recommendations

In addition to the applications in harsh nuclear environments discussed, SiC detectors have also been proposed for I&C of nuclear reactors for powering of deep-space missions [70] as well as for monitoring high-level radioactive waste reprocessing. [71]

SiC neutron detectors are an emerging technology which provides many advantages for monitoring harsh nuclear environments. SiC detectors can operate up to at least 700 °C and have been shown to withstand high doses of gamma-rays, neutrons and charged particles. Additionally, measurements have shown that irradiation of SiC at high temperatures reduces the radiation damage effects of the irradiation.

More elevated-temperature data are needed to understand the effects of temperature on mitigation of radiation damage in SiC. These effects are much more dramatic than those observed from post-irradiation annealing [55], and their understanding is crucially important for evaluating the applicability of SiC detectors in high-temperature, high-fluence nuclear environments.

It has been hypothesized [7] that so-called self-annealing operation may be possible with SiC detectors. If the rate of mitigation of radiation-induced damage at an elevated temperature is greater than or equal to the rate of introduction of radiation-induced damage, the effects of radiation should not limit the lifetimes of SiC detectors in that environment. Although an intriguing possibility, it remains to be demonstrated.

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Silicon Carbide Neutron Detectors for Harsh Nuclear Environments: A Review of the State of the Art

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***Abstract*— Silicon carbide (SiC) semiconductor is an ideal material for solid-state nuclear radiation detectors to be used in high-temperature, high-radiation environments. Such harsh environments are typically encountered in nuclear reactor measurement locations as well as high-level radioactive waste and/or "hot" dismantling-decommissioning operations. In the present fleet of commercial nuclear reactors, temperatures in excess of 300 °C are often encountered, and temperatures up to 800 °C are anticipated in advanced reactor designs. The wide bandgap for SiC (3.27 eV) compared to more widely used semiconductors such as silicon (1.12 eV at room temperature) has allowed low-noise measurements to be carried out at temperatures up to 700 °C. The concentration of thermally induced charge carriers in SiC at 700 °C is about four orders of magnitude less than that of silicon at room temperature. Furthermore, SiC radiation detectors have been demonstrated to be much more resistant to the effects of radiation-induced damage than more conventional semiconductors such as silicon, germanium, or cadmium zinc telluride (CZT), and have been demonstrated to be operational after extremely high gamma-ray, neutron, and charged-particle doses. The purpose of the present review is to provide an updated state of the art for SiC neutron detectors and to explore their applications in harsh high-temperature, high-radiation nuclear reactor applications. Conclusions related to the current state-of-the-art of SiC neutron detectors will be presented, and specific ideal applications will be discussed.**

***Index Terms*— Neutron detectors, silicon carbide, SiC, semiconductor, radiation damage**

I. Introduction

SILICON Carbide (SiC) semiconductor neutron detectors have many advantages for measurements in harsh high-temperature, high-radiation environments. The material properties of SiC, particularly the 4H polytype [1], make operation in these environments more feasible than for other conventional semiconductors such as Si, Ge, and CZT (Cadmium Zinc Telluride). The 3.27-eV bandgap for 4H SiC enables low-noise measurements at room temperature and temperatures up to at least 700 °C. SiC has also been shown to be resistant to the cumulative effects of gamma, neutron, and charged-particle irradiation. Other factors that are advantageous for SiC include:

- high thermal conductivity
- a maximum breakdown field that is eight times that of silicon allowing higher biases to be applied resulting in higher drift velocities and more efficient charge collection
- a high saturated drift velocity (nearly twice that of silicon) leading to low charge trapping

The use of SiC as a radiation detector material was reviewed by Nava, *et al.* in 2008 [1], Strokan, *et al.* in 2009 [2] and Ruddy in 2013 [3]. Designs and properties of SiC neutron detectors were reviewed by Franceschini and Ruddy in 2011 [4]. The purpose of the present review is to provide an updated state of the art for SiC neutron detectors and to explore their applications in harsh high-temperature, high-radiation nuclear reactor applications.

II. The History of Silicon Carbide Radiation Detector Development

SiC radiation detectors were first demonstrated more than sixty years ago. Initial results were first reported in 1957 [5] and summarized by Babcock and Chang in 1963 [6]. In their groundbreaking work, they demonstrated detection of alpha particles with SiC diodes at temperatures up to 700 °C using diodes produced by aluminum diffusion into SiC crystals grown by sublimation. Follow-on measurements by Ferber and Hamilton [7] used miniature neutron detectors formed by juxtaposing a ^{235}U layer near the sensitive volume of a SiC diode. They demonstrated a linear response to reactor power in the 10^7 to 10^{11} cm^{-2}-sec^{-1} neutron fluence-rate range and performed axial flux maps of a reactor at a fluence rate of 10^9 cm^{-2}-sec^{-1}. Good agreement was found with the results of gold-foil neutron activation dosimetry. The authors also reported that good alpha-particle spectrometry results were obtained with a SiC diode that had been exposed to a thermal neutron fluence of 6 x 10^{15} cm^{-2}.

Development of SiC radiation detectors was also carried out in the Soviet Union by Tikhomirova and co-workers using beryllium-doped 6H SiC. They measured an energy resolution

This paper was submitted for review on September 30, 2021.
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of 8% Full Width at Half Maximum (FWHM) for 4.5-MeV alpha particles. [8,9] Although they observed no degradation of the performance of a neutron detector using a ^{235}U convertor foil up to a thermal-neutron fluence of 5 x 10^{13} cm^{-2} , the detector performance decreased substantially at higher fluences.[10] The authors attributed this effect to neutron damage, but it is likely [4] that their diode performance was determined more by the effects of fission-fragment irradiation (approximately 7 x 10^{8} cm^{-2} fission fragments at a thermal-neutron fluence of 10^{13} cm^{-2}).

Further progress in SiC detector development was hindered by the lack of high-quality crystalline materials and techniques for applying electrical contacts. In the 1990's considerable progress was achieved in reducing SiC crystal defects such as dislocations, micropipes, *etc.*, introduced during the crystal growing process. Also, advanced epitaxial layer-growth technologies enabled the production of much higher quality SiC layers leading to a renewed interest in SiC as a detector material in 1995. The first SiC detectors based on high-quality SiC epitaxy were reported in 1998 by Ruddy, *et al.* [11]. Detectors based on both Schottky diode and p-n junction designs were demonstrated. The authors investigated temperature effects on the performance of the 4H-SiC radiation detectors and measured response to ^{238}Pu α-particles at several temperatures in the 22-89°C range. It was reported that no significant change of detector response was observed up to 89°C at a reverse bias of -20V. In follow-on work by Seshadri, *et al.* [12], a gradual degradation of charge collection efficiency of 4H-SiC Schottky diodes was observed above a thermal-neutron fluence of 5.7×10^{16} cm^{-2} (1.68×10^{16} cm^{-2}, E > 1 MeV) due to neutron-induced defects. It was noted that the observed degradation does not affect the counting characteristics but can limit the possibility of self-biased operation under high neutron fluences. Nevertheless, it was remarked that no significant degradation in the energy resolution was observed. Moreover, these detectors showed well resolved gamma-ray and alpha-particle signals. The obtained results demonstrated that 4H-SiC is a very promising material for applications in high radiation environments.

These initial results using epitaxial SiC diodes were confirmed by Nava, *et al.,*[13] who demonstrated ^{241}Am alpha particle detection with 4H SiC Schottky diodes and showed that charge collection efficiency increased linearly with the square root of the applied reverse bias.

Widespread interest in SiC radiation detectors ensued, and the initial results for alpha particles were rapidly followed by demonstration of detection of X-rays [14], minimum ionizing particles [15] and neutrons [16] using devices based on high-quality SiC epitaxial layers.

More recently, measurements for alpha, X-ray, and neutron detection with SiC detectors have produced results that are comparable to those that are attainable with silicon detectors. [17-23] For example, Mandal, Kleppinger and Chaudhuri [23] have obtained an energy resolution of 15.9 keV (FWHM) for 5486-keV ^{241}Am alpha particles and have calculated an intrinsic energy resolution of 10.5 keV. By comparison, silicon detectors routinely obtain an energy resolution of 10 keV, and the best obtained is 8 keV [24].

Detection of 14-MeV neutrons with SiC detectors [25] yielded reaction-peak energy resolutions that were virtually identical to those obtainable with silicon detectors. The peak widths corresponding to the ground and excited-state branches of the $^{28}Si(n,\alpha)^{25}Mg$ reaction were indistinguishable for SiC and silicon. Franceschini and Ruddy [26] noted that these widths were likely limited by the effects of reaction kinematics on the production of ionization in the Si and SiC detectors rather than on the characteristics of the detectors themselves. However, an alternative explanation is that the energy spread of the D-T source may have been the primary limiting factor for the observed peak resolutions.

It can be concluded that SiC detectors have evolved to a point that they are capable of being used as an alternative to silicon detectors in harsh environments where the use of the latter is prohibited by temperature and/or radiation damage constraints. Furthermore, SiC detectors can be expected to provide results in these harsh environments that are comparable to those obtainable with silicon detectors operating under ideal conditions.

III. SILICON CARBIDE DETECTOR DESIGNS

By far the most prevalent design for SiC nuclear detectors is the epitaxial layer design shown schematically in Fig. 1. [11-16,23] Although many different polytypes of SiC exist, 4H- SiC is most frequently used for nuclear applications as discussed in detail in reference [1]. The conducting SiC substrate depicted in Fig. 1 typically has a nitrogen dopant concentration of about

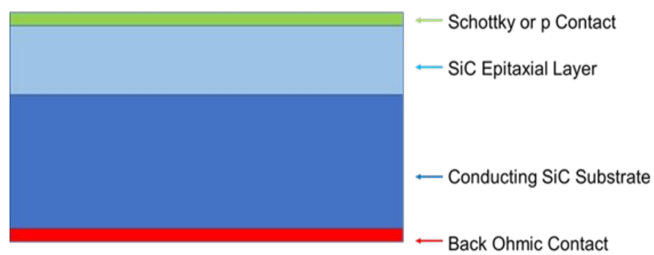

Fig. 1. Schematic representation of a SiC epitaxial diode detector structure.

10^{18} cm^{-3} and a thickness of about 300-350 µm. An n^- layer is grown onto the substrate layer using vapor-phase epitaxy. The dopant concentration in the epitaxial layer, which corresponds to the unintentional residual nitrogen concentration, is typically less than about 10^{15} cm^{-3}, and thicknesses ranging from a few µm up to 250 µm have been used. A metallic ohmic contact is applied to the back of the detector using a suitable material such as gold, titanium or nickel. The front contact can be either a Schottky contact using a suitable metal such as nickel or a p^+ contact formed by diffusing or implanting materials such as aluminum, phosphorus, or boron [11].

If a reverse bias is applied to the SiC diode as depicted in Fig. 2, charge carriers are depleted from the epitaxial layer, and this depleted or intrinsic SiC layer corresponds to the active layer of the detector.

The thickness of the depleted region, measured from the Schottky contact into the epitaxial layer, increases with reverse bias, V, according to the following approximation

$$d \cong \left[\frac{2\varepsilon V}{eN}\right]^{1/2} \quad (1)$$

where ε is the electrical permittivity for SiC, *e* is the electron charge and N is the effective doping concentration.

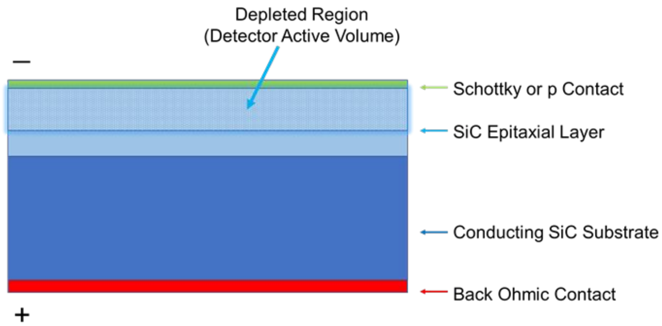

Fig. 2 Application of a reverse bias forms a depletion region in the epitaxial layer which corresponds to the active volume of the detector

It can be seen that the depletion thickness is directly proportional to the square root of the applied voltage and inversely proportional to the square root of the dopant concentration. The thickness of the depleted region for a typical diode is illustrated in Fig. 3. To achieve large active volumes

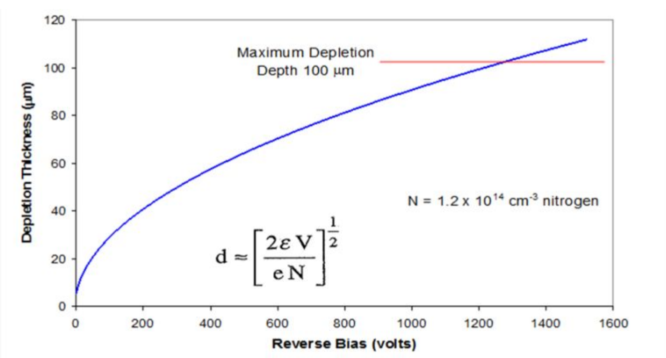

Fig. 3. Depletion depth as a function of applied reverse bias for a 100-µm thick epitaxial layer with a nitrogen concentration of 1.2 x 10^{14} cm^{-3}. The maximum depletion depth (horizontal red line) is the thickness of the epitaxial layer. A reverse bias of 1200 v is required for full depletion. If the reverse bias is limited to 1000 v, a 90-µm depletion depth results.

with thick epitaxial layers, one must have low nitrogen concentrations and/or apply high bias voltages. In practice, one might be constrained to voltages less than 1000 V (to protect the counting chain electronics from voltage discharges). Therefore, thick epitaxial layers with the lowest possible dopant concentrations are desirable. As discussed in reference [3], state-of-the-art SiC epitaxy is limited to nitrogen concentrations of about 10^{13} cm^{-3} , but a goal of 10^{12} cm^{-3} is reasonable [27].

IV. NEUTRON RESPONSE MEASUREMENTS

Neutrons have no electrical charge and are not capable of producing ionization directly in a detector. Therefore, as with all neutron detectors, SiC neutron detectors require a nuclear reaction to form reaction products that are capable of producing ionization within the detector active volume. For thermal-neutron detection, the following high cross-section nuclear reactions have proven useful: [4,28]

$^{10}B(n,\alpha)^{7}Li$	3840 barns
$^{6}Li(n,\alpha)^{3}H$	940 barns
$^{3}He(n,p)^{3}H$	5330 barns
^{235}U(n,f) fission products	585 barns

Compounds containing ^{10}B, ^{6}Li and ^{235}U have been used most frequently for thermal-neutron detection with SiC detectors, because solid-state compounds of these materials are readily available and can be configured to allow the energetic charged-particle reaction products to enter the detector active volume. [4,5-7,10,12,16] In practice, the thermal-neutron convertor material can be in the form of a thin layer juxtaposed near the active volume or can be incorporated into the detector by ion implantation [29] or diffusion [30].

Kandlakunta, *et al.*[31] have investigated the use of Nitrogen as a thermal neutron convertor using the $^{14}N(n,p)^{14}C$ reaction, which produces 584.0-keV protons. Although a clear response to protons was not demonstrated, Monte-Carlo response modelling of the response spectra of a SiC detector to neutrons in near-core reactor locations showed good agreement and correlated well with reactor power.

Fast neutrons can be detected by ionization produced by ions resulting from nuclear reactions with silicon or carbon atoms in or near to the SiC active volume of the detector. A partial list of reactions is shown in Table I. [4] Other more complex

TABLE I
FAST-NEUTRON INDUCED REACTIONS IN SILICON CARBIDE

Reaction	Threshold Energy (MeV)
$^{12}C(n,n')^{12}C$ (elastic scattering)	0
$^{28}Si(n,n')^{28}Si$ (elastic scattering)	0
$^{12}C(n,n')^{12}C$ (first excited state)	4.809
$^{28}Si(n,n')^{28}Si$ (first excited state)	1.843
$^{12}C(n,\alpha)^{9}Be$	6.180
$^{28}Si(n,\alpha)^{25}Mg$	2.749
$^{12}C(n,p)^{12}B$	13.643
$^{28}Si(n,p)$	3.999

reactions, such as (n,2n), (n,pn), (n,nα), *etc.* are also possible as well as reactions with less abundant isotopes of carbon and silicon. For fast-neutron spectra derived from energy moderation of fission neutrons, the response of a SiC detector will be dominated by the detection of energetic ^{12}C and ^{28}Si ions from (n,n') elastic and inelastic scattering reactions, because the average energy of fission neutrons is ~2 MeV with most of the neutrons having energies less than 6 MeV. Those threshold reactions that are energetically possible will add to the pulse-height continuum, because the incident neutron spectrum is a distribution of energies leading to a distribution of recoil-ion energies. A comparison of the thermal-neutron and fast-neutron responses for a SiC detector is shown in Fig. 4, which has been reproduced from Reference 32. Both spectra were taken for the same period of time at a reactor power of 500 watts.

When the ^{6}LiF converter foil is present, the detector response is dominated by the ^{4}He and ^{3}H ions produced by thermal-neutron reactions. Although events from fast-neutron induced reactions are present in the spectrum, they are obscured by the thermal neutron-induced events, which are much more abundant.

The fast-neutron spectrum (no converter foil) shown in Fig. 4 is a continuum dominated by elastic and inelastic neutron scattering reactions with carbon and silicon atoms in the SiC detector as discussed previously. The events below channel 300 are due primarily to gamma-ray induced secondary-electrons.

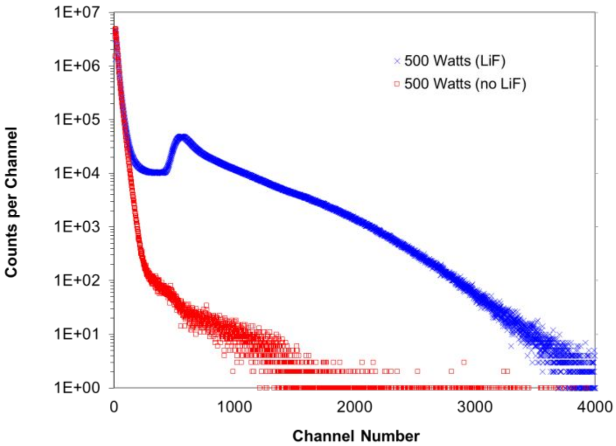

Fig. 4. Comparison of the neutron response of a 500-µm diameter x 3-µm SiC Schottky diode to reactor fission neutrons with and without a 24.2-µm ^{6}LiF convertor foil. With the ^{6}LiF foil present, the detector response is primarily to thermal neutrons When the ^{6}LiF foil is absent, the detector responds primarily to fast neutrons. (Figure reproduced from Reference 32).

The ranges of these electrons in SiC are large compared to the dimensions of the detector active volume resulting in only a fraction of the energy from each being detected. Although only a featureless low-energy continuum results, the detector response to gamma rays has been shown to be linear. [33-35] The fast-neutron response is complex and results in no peaks in the spectrum. Nevertheless, incident neutron energy information is present as shown by the data in Fig 5. [25].

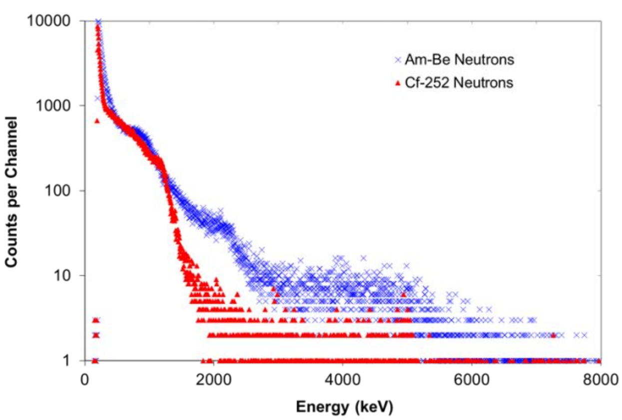

Fig. 5. Comparison of the responses of a SiC detector to fission neutrons from ^{252}Cf and neutrons from an ^{241}Am-beryllium source. (Adapted from reference 25)

The average energy of neutrons from fission of ^{252}Cf is 2.15 MeV, whereas the ^{241}Am-Be source produces a much higher average energy of 4.5 MeV. The ^{241}Am-Be detector response continuum is clearly shifted to higher pulse heights compared to the ^{252}Cf response spectrum. This effect is also apparent in the data of Fig. 6, where the responses to neutrons from ^{252}Cf spontaneous fission decay and neutron-induced ^{235}U fission are compared. [36] The average neutron energy from ^{252}Cf spontaneous fission decay is 2.15 MeV and the average energy from thermal-neutron induced fission of ^{235}U is 2.5 MeV, and the latter spectrum is shifted to higher energies compared to the former.

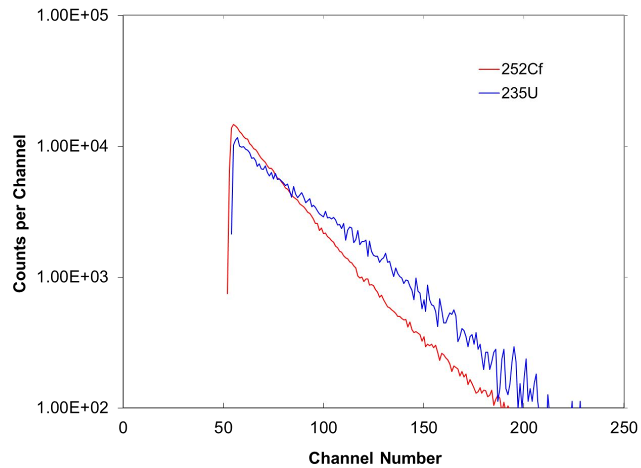

Fig. 6. Comparison of the response spectra of a SiC detector to neutron-induced fission neutrons from ^{235}U and ^{252}Cf spontaneous fission neutrons. (Adapted from Reference 36)

In order to extract neutron-spectrum information from the pulse-height response, a complex unfolding procedure using a combination of neutron transport and recoil range calculations is required. The calculations of Reference 26 for the monoenergetic 14-MeV neutron response spectrum of a SiC detector are a promising start towards this goal.

In the case of monoenergetic neutrons impinging on a SiC detector, peaks will be present for those reactions that result only in charged-particle products. For example, the $^{12}C(n,\alpha)$ reaction (see Table I) results only in ^{4}He and ^{9}Be ions which share the energy of the incident neutron plus the reaction energy. Therefore, a peak will be observed corresponding to ionization resulting from a total energy of 8298.8 keV being deposited in the detector active volume. The response spectrum for a SiC detector exposed to 14.1 MeV neutrons from a Deuterium-Tritium (DT) neutron generator is shown in Fig. 7, which has been reproduced from Reference 25.

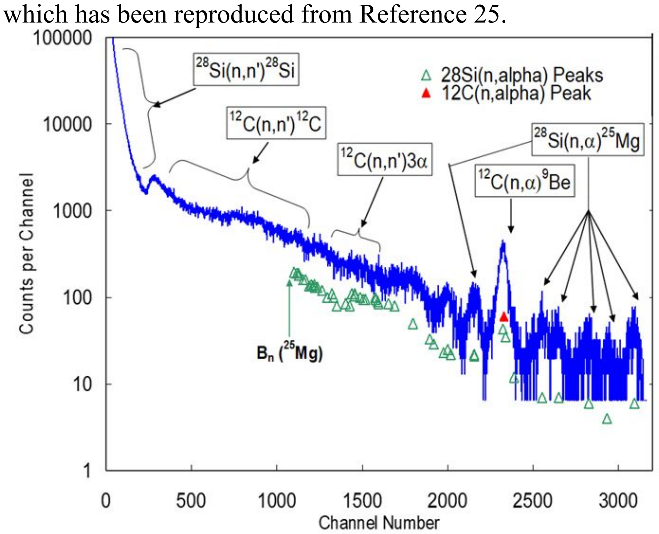

Fig. 7. Response spectrum for a 6 mm^{2} x 100 µm SiC detector exposed to 14.1 MeV DT neutrons. (Reproduced from Reference 25)

In addition to the prominent peak from the $^{12}C(n,\alpha)^{9}Be$ reaction, a family of peaks corresponding to the $^{28}Si(n,\alpha)^{25}Mg$ reaction is also present. The highest-energy peak corresponds to the production of the ground state of ^{25}Mg with the deposition of a total energy of 11,346 keV in the SiC detector active volume. The other peaks in this set correspond to excited states of ^{25}Mg where less energy is deposited in the detector. The difference in energy corresponds to gamma rays produced when these excited states of ^{25}Mg decay to the ground state. As the energies of these excited states increases, the energy spacing between them decreases, and the peaks are not resolved above about the tenth excited state. The higher energy states will produce a continuum of events up to the ^{25}Mg neutron binding energy, B_n, above which the $^{28}Si(n,n'\alpha)^{24}Mg$ reaction will dominate. Since the energy of the neutron produced in this reaction is not fixed, no peaks will result from this reaction.

Notably absent are peaks corresponding to the $^{28}Si(n,p)$ and $^{12}C(n,p)$ reactions. The protons produced in these reactions have energies that results in ranges in SiC that are much larger than the thickness of the detector active volume. Therefore, only a varying fraction of the energy from these reactions is deposited in the active volume, and the peaks are obscured by this finite detector volume effect [25,26].

Continua from elastic and inelastic neutron scattering as well as more complex reactions such as $^{12}C(n,n')3\alpha$ are also present. No single peak is observed for these reactions, because the energy of the reaction product neutron is not fixed.

The neutron responses for SiC detectors have been shown to be linear for thermal [16], epithermal [33,34], fast [32] and 14-MeV neutrons [37]. Furthermore, the neutron response is separable on the basis of pulse height from the gross gamma-ray response [12,16,33], and gamma-ray response has also been shown to be linear [33-35].

V. NEUTRON-RESPONSE MEASUREMENTS AT HIGH TEMPERATURES

Some applications such as fusion-reactor technologies require stable measurement methods to detect neutrons and charged particles under extreme conditions such as high temperatures and high magnetic fields. To maintain the fusion process, it is mandatory to measure simultaneously the neutron flux and the tritium breeding ratio.

Specific fast neutron detectors, based on 4H-SiC pn diodes, were developed in the framework of the European I_SMART project [38]. The characteristics of these detectors were measured at room temperature and compared with a single-crystal chemical vapor deposited (sCVD) diamond-based detector (purchased from CIVIDEC Instrumentation Company). Measurements were carried out at the DT neutron generator at Technical University of Dresden (TUD). The detectors were positioned at 13 cm away from the tritium target at an angle of 90° with respect to the deuteron beam. The neutron fluence rate at this point was calculated to be about 9.4×10^{6} cm^{-2}-s^{-1} with a neutron energy of 14.12 MeV.

Fig. 8 shows that both detectors produce pulse-height spectra with the well-resolved peak due to the $^{12}C(n,\alpha)^{9}Be$ reaction. The count rate of the diamond-based detector is higher than that of the SiC-based detector as a consequence of the higher thickness of the diamond active detection volume. The energy resolution of this peak is slightly better for the 4H-SiC-based detector (260 keV at FWHM which corresponds to 3.09%), with respect to 303 keV (3.6%) for the diamond detector. An important phenomenon is the improvement of the energy resolution with increased neutron flux for the SiC detector, in complete opposition to the behavior of diamond [38]. The cause of this behavior is not understood at this time.

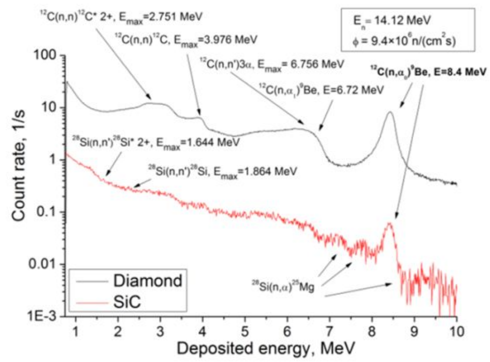

Fig. 8. Comparison of the responses of SiC-based and CVD diamond-based detectors to 14.12 MeV neutrons. (Figure reproduced from Reference [38].)

Several prototypes were also tested in industrial conditions at the fast neutron generator at Schlumberger (Clamart, France), at room temperature and at 106 ° C [39]. The spectra show good stability, preserving features over the whole temperature range. Prototypes with gold metallic contacts were then tested up to 500 °C at the DT neutron generator at the TUD [40]. In the recorded spectra, the different signal structures arising from high-energy deep inelastic reactions can be distinguished, independently of the temperature (see Fig. 9). The most prominent orientation point in the spectrum is the full energy peak of the $^{12}C(n,\alpha)^{9}Be$ reaction, which can be clearly distinguished at all the applied temperatures.

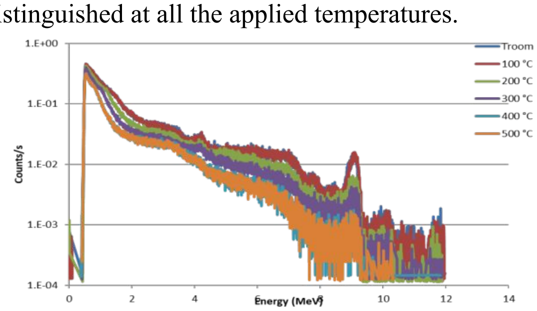

Fig. 9. Energy spectra recorded during irradiation tests of SiC-based detectors with 14 MeV neutrons at different ambient temperatures. (Figure reproduced from reference 40).

Abubakar, *et al.* [41] reported stability of the SiC-based alpha detector signal at 500 K (227 °C) over a period of 18 hours.

Wang, *et al.*[42] performed measurements of the response of a SiC detector to a weak ^{241}Am alpha-particle source in the presence of an intense ^{60}Co gamma-ray background and observed some degradation of the alpha energy resolution due to pulse pile up and secondary trapping effects. At temperatures up to 500 °C, only slightly degraded energy resolution was observed. Stable SiC spectral responses were observed during ~2-hour gamma-ray, neutron-beam and near-core irradiations.

No temperature-induced polarization effect has been observed to date with epitaxial Silicon Carbide, in contrast to the case of diamond where this effect appears above 600 K (327 °C) [43].

VI. RADIATION DAMAGE EFFECTS IN SILICON CARBIDE DETECTORS

Whereas conventional neutron detectors such as fission chambers and self-powered neutron detectors exhibit excellent resistance to the cumulative damaging effects of radiation, some monitoring applications are potentially better suited to semiconductor detectors. Common semiconductor detectors based on silicon or germanium are not only limited to low-temperature operation, because of low band gaps, but also have low service lifetimes due to radiation damage effects. Therefore, these detectors have been of little use in harsh nuclear environments where large doses of gamma rays, neutrons and charged particles must be tolerated.

For example, silicon detectors show increasing leakage current when exposed to radiation due to the formation of defects that correspond to charge-donor levels in the band gap. Charge-trapping sites are also produced, but the increased leakage current is the primary radiation-damage limitation for the use of silicon detectors and is an indirect consequence of the low band gap for silicon.

On the other hand, wide band-gap semiconductor detectors such as SiC are limited more by the accumulation of charge-trapping sites. Increased leakage current due to the formation of charge-donor states is less due to the larger band gap.

SiC has been shown to be highly resistant to the effects of radiation damage. The effects of large gamma-ray doses on the performance of SiC detectors have been investigated by several groups. Kang, *et al.* [44] showed that irradiating 6H SiC diodes with a dose of 120 kGy of ^{60}Co gamma rays leads to a leakage-current decrease. Metzger, *et al.* [45], observed no change in the ^{60}Co gamma-ray detection efficiency of 6H SiC photodiodes after a 1.080 MGy dose of ^{60}Co gamma rays, and Kinoshita, *et al.*[46], observed no change in the 100% charge-collection efficiency of 6H SiC p-n diodes after a ^{60}Co gamma-ray dose of 2.5 MGy. Ruddy and Seidel [47,48] irradiated 4H SiC Schottky diodes to a cumulative ^{137}Cs gamma-ray dose of 22.7 MGy. ^{137}Cs gamma rays were used to simulate the radiation environment of spent-fuel assembly five years after discharge from a nuclear power reactor. Photographs of the 6-mm^2 x 100-µm diode before and after the irradiation are shown in Fig. 10.

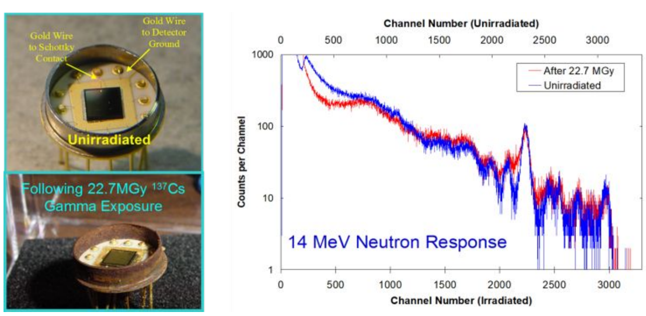

Fig. 10. Photographs of a 6-mm^2 x 100-µm SiC Schottky diode before (top) and after (bottom) exposure to a cumulative ^{137}Cs gamma-ray dose of 22.7 MGy and comparison of the corresponding neutron responses (Figures adapted from reference 48)

The irradiation was carried out in a dry-Nitrogen environment to minimize corrosion and other chemical/radiolytical effects on the detector. Although the physical damage effects of the gamma-ray exposure on the detector are apparent from the photos, the irradiated detector was found to perform well as a detector for fast ^{252}Cf fission neutrons and for 14-Mev D-T neutrons [48]. The 14-MeV neutron response spectrum for the irradiated detector is compared to an identical unirradiated detector in Fig. 10. The observed difference between the before- and after-irradiation spectra are minor. Although a higher operating voltage was required for the irradiated-detector spectrum, the ^{12}C(n,α)^{9}Be and ^{28}Si(n,α)^{25}Mg reaction peaks are apparent in both spectra.

Whereas the radiation effects of gamma rays on the response and operational lifetimes of SiC detectors are minor, the effects of charged particle and fast neutron damage are more formidable. For SiC detectors exposed in neutron environments, the radiation effects of fast neutrons as well as the charged particles produced by neutron convertor reactions (*e.g.,* ^{6}Li[n,α]^{3}H), ^{10}B[n,α]^{7}Li, ^{235}U[n,f]) are both primary concerns. As noted previously in Section 2.0 of this manuscript, Tikhomirova, *et al.* [10] noted degradation of Beryllium-doped 6H SiC detectors at thermal-neutron fluences greater than 10^{13} cm^{-2} for devices using a uranium convertor foil. However, the degradation was more likely due to the fission product ions from the convertor foil than from the neutrons impinging on the detector.

An early neutron-damage study carried out by Ferber and Hamilton [7] showed that good alpha-particle spectrometry results were obtained with a SiC diode equipped with a ^{235}U convertor foil that had been exposed to a thermal neutron fluence of 6 x 10^{15} cm^{-2}. However, the fast-neutron fluence was not reported, and any radiation damage to the detector would have been caused by fast neutrons and fission fragments.

Dulloo, *et al.,* [16, 49] showed that the thermal-neutron response of a SiC Schottky diode with a ^{6}LiF convertor foil was indistinguishable from that of an unirradiated detector after a fast-neutron (E >1 MeV) fluence of 1.3 x 10^{16} cm^{-2}.

Lo Giudice , *et al.,* [50] irradiated large area 4H-SiC Schottky diodes equipped with a ^{6}LiF convertors with epithermal neutrons and observed less than 0.3% decrease in the count rate after a neutron fluence of 10^{13} cm^{-2}. They attributed this minor decrease to alpha-particle damage from the ^{6}Li(n,α)^{3}H convertor layer. The more energetic ^{3}H ions would be expected to produce less localized damage.

Afanasyev, *et al.,* [51] examined the photosensitivity of SiC UV photodiodes and observed no change in performance after a fast-neutron fluence of 5 x 10^{12} cm^{-2}, but observed degradation of I-V-characteristics, reduction of carrier lifetimes and, as a result, reduction of the photosensitivity of their devices at higher fluences up to 1 x 10^{14} cm^{-2}. They attributed the performance changes to the creation of deep recombination centers, which will interfere with charge collection.

Nava, *et al.,* [52] performed a comprehensive study of the detection properties of 4H SiC Schottky diodes irradiated with 1 MeV neutron fluences up to 8 x 10^{15} cm^{-2}. They observed only minor (~20%) losses in charge-collection efficiency at fluences up to 10^{15} cm^{-2} , which they attribute to the detector behaving more as “intrinsic” SiC material due to compensation of the dopant atoms by traps. At fluences higher than 10^{15} cm^{-2} the charge-collection losses increase monotonically to ~80% loss at 8 x 10^{15} cm^{-2}. They attributed the degradation to the production of two types of deep-level traps, which correspond to neutron-induced carbon and silicon vacancies.

An earlier study by Seshadri, *et al.,* [12] reached a similar conclusion. They found that the charge collection efficiency for ^{238}Pu alpha particles decreased systematically, and that self-biased operation was not possible following an accumulated fast-neutron (E > 1 MeV) fluence of 5.7 x 10^{16} cm^{-2}. The reduction in charge-collection efficiency was systematic and corresponded to a carrier removal rate of 9.7±0.7 cm^{-1}, which the authors attributed to the introduction of deep-level traps by fast-neutron interactions.

A later study by Wu, *et al.* [53] found that the charge collection efficiency for self-biased 4H SiC Schottky diodes reduced to 1.3% of the unirradiated value after irradiation with a fast-neutron fluence of 8.26 x 10^{14} cm^{-2}.

Liu, *et al.* [54] compared the performance of Si and SiC neutron detectors following irradiations with 14.86-MeV neutrons from a D-T accelerator. They observed more than four orders of magnitude increase in the Si detector dark current and a severe reduction (over 95%) in the ^{239}Pu α peak centroid position after a D-T neutron fluence of 1.65 x 10^{13} cm^{-2}. The SiC neutron detector showed nearly no degradation up to a higher fluence of 3.82 x 10^{13} cm^{-2}.

Systematic investigations were made by Ruddy, *et al.,* [55] of the effects on detector performance of both fast (E > 1 MeV) neutrons and energetic ^{3}H and ^{4}He ions from reactions in a ^{6}LiF convertor layer. SiC pn and Schottky diodes with 200 µm diameters and 8- µm epitaxial layers with a nitrogen dopant concentration 1 x 10^{15} cm^{-3} as described in Reference [11] were irradiated in three configurations. Detectors with a juxtaposed ^{6}LiF convertor layer, with a 6- µm aluminum foil between the detector and the ^{6}Lif layer, and with no convertor layer were irradiated to evaluate the effects of neutrons plus ^{3}H plus ^{4}He, neutrons plus ^{3}H, and neutrons only, respectively. Following irradiation, the detectors were tested with a ^{238}Pu alpha-particle source as described in Reference [11] in order to evaluate charge-collection efficiency as a function of accumulated neutron and charged-particle fluence. The pulse-height response of the three detector configurations after a thermal-neutron fluence of 3.9 x 10^{16} cm^{-2} is shown in Fig. 11.

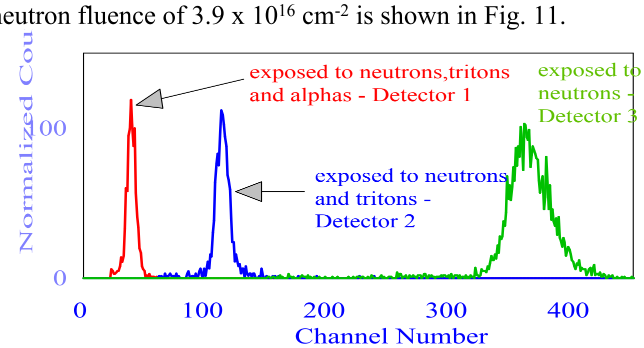

Fig. 11. Comparison of the ^{238}Pu pulse-height response of three detector configurations following irradiation. (Figure reproduced from Reference 55)

In all three cases, the pulse height is reduced following irradiation. As expected, the largest shift is obtained for the case where the detector is exposed to neutrons plus ^{3}H and ^{4}He, the lowest shift is for neutrons only, and an intermediate shift is obtained for neutrons plus ^{3}H. The observed pulse-heights decreased with increasing neutron fluence for all three configurations. For detectors exposed to neutrons only, a rapid decrease was observed up to a fast-neutron fluence of about 10^{14} cm^{-2}, followed by a much more gradual decrease at higher fluences. This was attributed [55] to the introduction of charge-trapping sites corresponding to a carrier removal rate of 9.7 cm^{-1} as measured in Reference [12] until the nitrogen doping concentration of 10^{15} cm^{-3} was fully compensated. After full compensation, the SiC behaves as intrinsic material [55].

Based on a simple first-order model of charge-carrier loss as a function of charge-trap density [56], it was shown [55] that the observed pulse height should be proportional to the reciprocal of the accumulated fast-neutron fluence. Such a plot for the observed pulse heights for an irradiated SiC detector with no convertor layer (neutron damage only) is shown in Fig. 12.

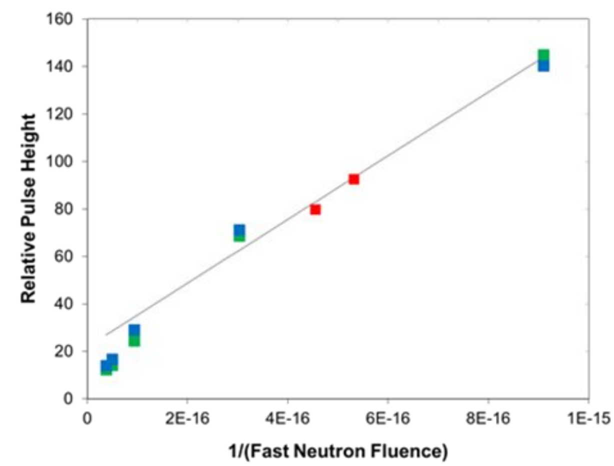

Fig. 12 ^{238}Pu pulse heights for SiC diodes exposed to fast neutrons. Pulse height is plotted as a function of reciprocal fast-neutron fluence. (Figure reproduced from Reference [55])

The fast-neutron fluence corresponding to the lowest observed pulse height in Fig. 12 is 1.1 x 10^{17} n cm^{-2}. The ambient reactor temperature in the irradiation position was 45 °C. An approximate linear relationship between pulse height and reciprocal fast-neutron fluence is observed over the entire range of the measurements, consistent with the predictions [12,55,56] of the simple first-order model which assumes that loss of charge carriers is directly proportional to the density of charge traps produced in the SiC.

A similar plot for the cases where a ^{6}LiF foil with (n + ^{3}H) and without (n + ^{3}H + He^{4}) an aluminum absorber adjacent to the SiC diodes during irradiation is shown in Fig. 13. Rather

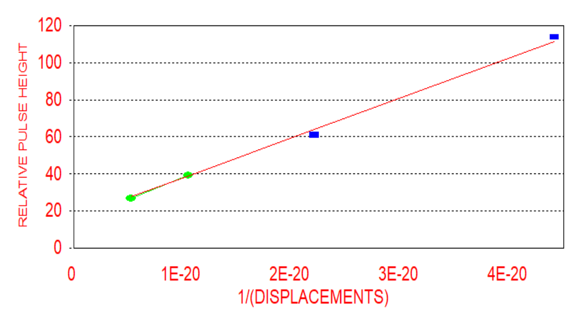

Fig. 13 ^{238}Pu pulse heights for SiC diodes exposed to fast neutrons and neutron reaction-product ions. Pulse height is plotted as a function of reciprocal calculated displacements. The ovals correspond to neutron plus triton plus alpha-particle exposures and the squares correspond to neutron plus triton exposures (Figure reproduced from Reference [55]) than neutron fluence, calculated displacements were used to account for the relative damage produced by neutrons and tritons. Again, a straight-line relationship is observed over the entire range of the irradiations which were carried out at 45 °C.

In all cases, although the alpha-response peak centroid was shifted, the detector count rate for alpha-induced events was unaffected for the exposure ranges studied, and the signals for gamma and alpha radiation were still separable. [55]

It was observed by McLean, *et al.* [57] that the effects of neutron irradiation on 6H SiC JFETs were less severe if the irradiation occurs at higher temperatures. They observed a change in the carrier removal rate from 3.5 cm^{-1} at room temperature to 4.75 cm^{-1} at 300 °C. Scozzie, *et al.* [58] observed no onset of JFET performance changes up to a neutron fluence of 1 x 10^{15} cm^{-2} at room temperature. Irradiation at 300 °C extended the onset of changes to 5 x 10^{15} cm^{-2}. It was concluded [58] that elevated temperature irradiation mitigates the effects of the irradiation-induced damage.

This potential effect was investigated by Ruddy, *et al,* [55] who performed further irradiations at 230 °C. The data for neutrons-only irradiations at 230 °C and 45 °C are compared in Fig. 14. The results at both temperatures are fit well by a

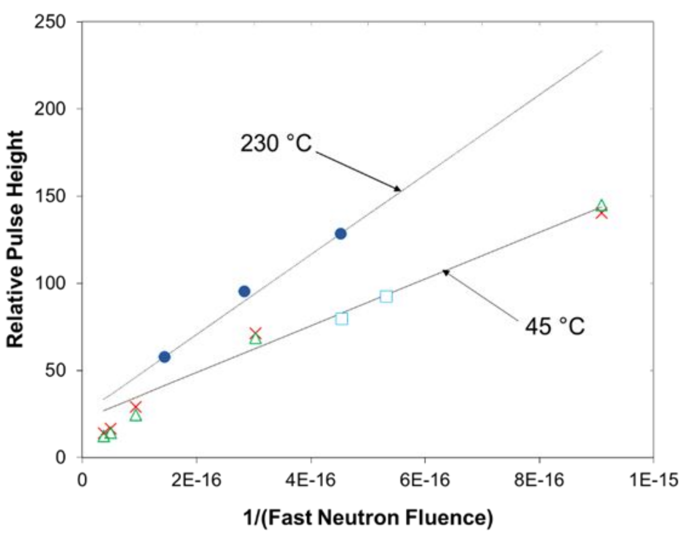

Fig. 14. Effect of elevated temperature during neutron irradiation on the observed pulse heights from a ^{238}Pu alpha test source. Pulse height is plotted as a function of reciprocal fast neutron fluence. The symbols refer to different irradiated SiC detectors. (Figure adapted from Reference 55)

straight line, consistent with the predictions [12,55,56] of a simple first-order model which assumes that loss of charge carriers is directly proportional to the density of charge traps produced in the SiC active volume by fast neutrons. A similar relationship was observed for the charged-particle results at 230 °C, where ^{238}Pu pulse height was found to be proportional to the reciprocal of the calculated displacements caused by the fast neutrons, ^{3}H ions and ^{4}He ions

It can be seen from Fig. 14 that the 230 °C irradiations produce significantly higher charge collection than the 45 °C irradiations. It was concluded by the authors [55] that elevated temperature mitigates the effects of the radiation damage on charge collection, but that more data are needed at temperatures of 300 °C and higher. An important implication of these results is that operation in an elevated-temperature environment may significantly *extend* the service lifetime of a SiC neutron detector.

The mechanisms involved in mitigation of radiation damage effects during elevated-temperature irradiations are not clear at present due to the paucity of elevated-temperature data. More data are needed to better understand this phenomenon, which is potentially beneficial for SiC detector applications in harsh environments.

VII. Applications in Harsh Nuclear Environments

Selected potential harsh-environment applications of SiC neutron detectors are discussed in the following sections.

A. Spent Fuel Monitoring

Although monitoring of spent fuel does not involve temperatures significantly above room temperature, extremely harsh gamma-ray environments with high gamma-ray to neutron ratios are generally encountered. During reactor irradiation, nuclear fuel acquires a neutron specific activity, primarily due to the buildup of higher actinides by successive neutron reactions originating with the ^{238}U component of the fuel. [33-35] These actinides produce neutrons through spontaneous fission of isotopes such as ^{240}Pu, ^{242}Cm and ^{244}Cm. During the first operating cycle, ^{240}Pu will dominate, but for a fully burnt fuel assembly several years after discharge, the primary neutron-producing isotope will be 18.1-year ^{244}Cm. In the case of oxide fuels, neutrons are also produced by the alpha-emitters present through $^{18}O(\alpha,n)$ and $^{17}O(\alpha,n)$ reactions. Gamma rays will also be present primarily from the fission-product inventory present in the fuel. For example, a Pressurized Water Reactor (PWR) fuel assembly with a burnup of 25,655 MWd/MTU had a total surface neutron fluence rate of 8000 cm^{-2}-s^{-1} at midplane three years after discharge [59], and typical gamma dose rates in spent-fuel environments are in the 10^{2} -10^{3} Gy/hr range [34-35].

Natsume, *et al.*, [35] tested a SiC neutron detector in a spent fuel pool, and over a 2050-hour (85.4-day) period of continuous monitoring the detector neutron and gamma response did not change or deteriorate. At the detector location, the fluence rates were 180 cm^{-2}-s^{-1} and 11 Gy/hr for fast neutrons and gamma rays, respectively. Both the gamma-ray and neutron count rates, which were separable on the basis of pulse height, were stable to a precision of 1.7% and 2.9% for gamma rays and neutrons, respectively. [35]

The high radiation resistance, stability in elevated and changing temperatures and small size and versatility of SiC detectors make them extremely useful for spent-fuel monitoring applications.

B. Safeguards Monitoring

A related safeguards-monitoring application is long-term monitoring of spent fuel. The axial distribution of the neutron emission rate at the surface of a spent fuel assembly will depend on the burnup history of the assembly as shown in Fig. 15. [59]. The neutron fluence rates calculated from the measured ^{235}U (bare and cadmium covered), ^{238}U, and ^{237}Np fission rates are plotted as a function of axial location on the assembly face. The fast-neutron fluence rates show axial variations which reflect the local fuel burnup history. The thermal- and epithermal-

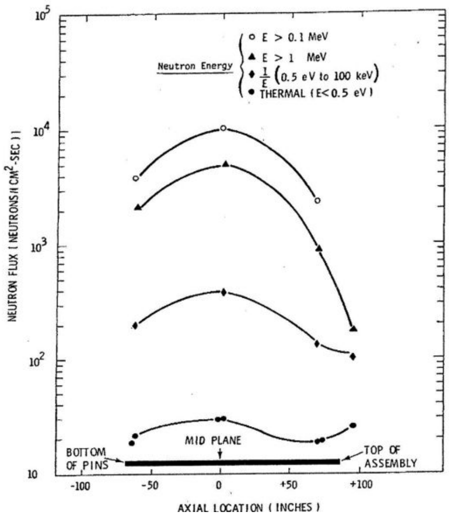

Fig. 15 Axial neutron fluence rate distributions for a typical PWR spent-fuel assembly (Figure reproduced from Reference [59].

neutron fluence rate axial distributions were influenced by room-return (*e.g.,* neutron energy moderation in the walls of the hot cell where the measurements were carried out) and reflect the local environment as well as the characteristics of the fuel assembly resulting in flatter axial distributions. [59]

SiC neutron detectors can be used to monitor thermal and epithermal neutron fluence rates as well as the fast-neutron energy spectrum as a function of axial position either by affixing detectors near the surface of the assembly or inserting a stringer of detectors within an assembly guide tube. SiC neutron detectors can be used for measurements within spent-fuel shipment or storage casks. Deviations from the expected neutron energy spectra or spatial distributions can be used as an indicator of off-normal conditions resulting from, for example:

- diversion of fuel rods – reduced neutron fluence rates will be observed near the missing rod location.
- mechanical or corrosive deterioration of the assembly will perturb the measured distribution of neutron fluence rates.
- water incursion – increased neutron thermalization will be observed due to the moderating effect of the water

It has been demonstrated [55] that after a fast (E>1MeV) fluence of 1.7 x 10^{17} cm^{-2}, SiC neutron detectors are still functional. In a typical spent fuel neutron environment, it would take 5-50 million years to reach this dose. It has also been shown that SiC detectors operate well after a ^{137}Cs dose of 22.7 MGy [48]. If a SiC detector were to be placed adjacent to or within a spent fuel assembly immediately after discharge and left in place indefinitely, this dose would *never* be reached.

Therefore, SiC neutron detectors are capable of continuously monitoring a spent fuel assembly following discharge from the reactor, during transportation and following deposition in a spent fuel repository.

C. Monitoring of Nuclear Fusion Devices

Monitoring of nuclear fusion devices and reactors is required to obtain information on important operational parameters such as fusion power and plasma temperature. In a fusion power reactor, such as the International Thermonuclear Experimental Reactor (ITER) currently under construction in Cadarache, France, the neutron intensity and energy distribution can be used to deduce information on the fusion power and ion temperature [60].

A schematic representation of a Tokamak fusion reactor with tritium-breeding capabilities is shown in Fig. 16.

Fusion is produced in a dense, high-temperature, magnetically confined plasma. The primary energy-producing reaction is

$$^{3}H + {}^{2}H \rightarrow {}^{4}He + n \quad (E_n = 14.1\ MeV),$$

But the following reactions are also taking place:

$$^{2}H + {}^{2}H \rightarrow {}^{3}He + n \quad (E_n = 2.5\ MeV)$$
$$^{2}H + {}^{2}H \rightarrow {}^{3}H + {}^{1}H$$

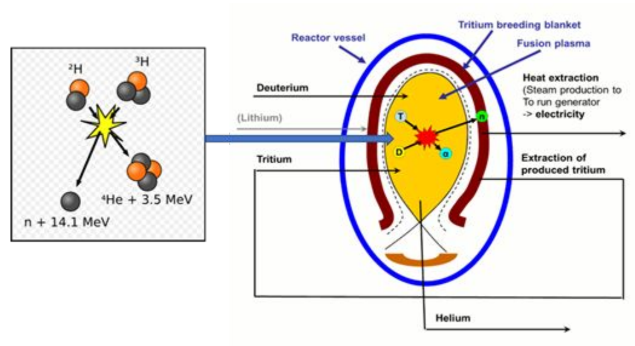

Fig. 16. Schematic representation of a Tokamak nuclear fusion reactor.

as well as other secondary ion reactions. The plasma and its surroundings are an extremely harsh measurement environment with temperatures exceeding 150,000,000 °C. In Test Blanket Modules (TBMs) in the ITER wall, temperatures can reach up to 920 °C in the breeder material, up to 550 °C in the EUROFER structure, and up to 650 °C in the neutron multiplier. Magnetic fields of ~4T are present and measurements must be carried out with extremely limited access/space.

SiC neutron detectors are potentially capable of providing detailed neutron spectra under these conditions as discussed in Sections IV-V. Peaks from $^{12}C(n,\alpha)^{9}Be$ and $^{28}Si(n,\alpha)^{25}Mg$ reactions can provide information on the D-T fusion energy as well its energy width. The reaction peaks can be measured to an energy resolution of 2.2-2.3% FWHM, equal to the energy resolution obtainable with Si detectors [25], which have no prospects for operating in a fusion reactor environment.

SiC detectors have been proposed and are being tested for in-vessel tokamak measurements [61], and promising preliminary results have been obtained.

Concepts are also being developed to demonstrate on-line breeding of tritium to fuel the fusion reaction. TBMs integrated inside the tokamak wall will produce tritium from lithium via the following reactions:

$$^{6}Li + n_{th} \rightarrow {}^{3}H + {}^{4}He \quad (Q = 4.78\ MeV)$$
$$^{7}Li + n \rightarrow {}^{3}H + {}^{4}He + n$$

SiC neutron detectors can be used to monitor the thermal-neutron fluence rate at key locations in and around the TBMs. If a LiF convertor is used, the detector count-rate is a direct measure of the tritium production reaction rate.

Indeed, SiC has been proposed as a candidate detector for TBMs and is undergoing testing. [40]

In addition to neutron measurements, SiC charged-particle detectors can be deployed to obtain information on yields of charged particles (^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He) from fusion and breeder reactions.

D. Monitoring of Test and Research Reactors

Advanced test and research reactors are coming online to address new requirements that can not be met by the current aging fleet. An example is the Jules Horowitz Reactor (JHR), which is currently under construction at CEA Cadarache, France [62]. These reactors will address nuclear materials and fuels irradiation testing needs being generated by advanced commercial nuclear power plant designs that employ innovative high-temperature coolants such as liquid metals and molten salts. Neutron monitoring is required for testing in the high-temperature and high fluence-rate environments typical of reactors such as JHR.

In the framework of the European I_SMART project [63], new 4H-SiC based neutron detectors were developed and tested and have been demonstrated to be able to operate in harsh environments and detect both fast and thermal neutrons. [64-66] Prototypes with various designs were fabricated, some of them optimized for thermal neutron detection via a specific boron converter layer (either deposited on top of the structure or implanted in the anode ohmic contact layer). These detectors have been tested at the MINERVE zero power reactor and in the SCK•CEN BR1 reactor (at fluence rates of the order of 10^9 cm^{-2}-s^{-1}) using prototypes of various sizes, with and without ^{10}B (implanted at room temperature or at 400 °C). These measurements proved the linearity of the detector responses with reactor power. In addition, thermal neutron detection spectra were recorded as a function of bias voltage. Zero bias operation was demonstrated and shown to give the best gamma-ray discrimination consistent with the thin active volume produced by the zero-bias p-n diode potential.

Tests are planned in the Joseph Stefan Institute TRIGA reactor at fluence rates of the order of 10^{12} cm^{-2}-sec^{-1}, leading to high fluence and fluence-rate testing at the 100-MW JHR.

E. Monitoring of Advanced Nuclear Power Reactors

Many of the advanced nuclear power reactors under development utilize extremely high-temperature coolant concepts. See, for example Reference [67]. TERRAPOWER's Natrium Reactor is a sodium-cooled fast reactor with a molten-salt energy storage system. Kairos Power's KP-FHR reactor employs fluoride-salt cooling, and Southern Company's Molten Chloride Reactor also requires molten-salt cooling. High-temperature gas reactor designs, such as X-Energy's XE-100 also involve high operating temperatures. These reactors under development will require neutron monitoring at temperatures up to 850 ° C and will present challenges to the present gas-filled and self-powered neutron detector technology. SiC neutron detectors have been demonstrated at temperatures up to 700 °C and likely can operate at much higher temperatures (4H SiC sublimes at 2857 °C).

SiC neutron detectors have been proposed [68] as an alternative to the gas-filled neutron detector reactor power monitors used in the current fleet of PWRs and Boiling Water Reactors as well as for a proposed advanced PWR design. [69] Among the advantages identified are wider dynamic range, elimination of gamma compensation, and improved reliability of supply. Whereas implementation and qualification of completely new power monitoring systems is extremely difficult in power reactors that are currently in operation, development of advanced water-cooled reactors, such as Holtech International's SMR-160 (an advanced light-water small modular reactor) and Westinghouse's eVinci (a heat pipe-cooled microreactor) as well as the BWXT Advanced High-Temperature Gas-Cooled microreactor [67] will likely require new and innovative neutron detectors for reactor power monitoring instrumentation and control (I&C). Implementation of traditional gas-filled neutron detectors may be cumbersome or even impossible in these new reactor designs. I&C systems based on SiC neutron detectors provide an alternative which can improve the reliability and practicality of these small and micro reactors.

VIII. CONCLUSIONS AND RECOMMENDATIONS

In addition to the applications in harsh nuclear environments discussed, SiC detectors have also been proposed for I&C of nuclear reactors for powering of deep-space missions [70] as well as for monitoring high-level radioactive waste reprocessing. [71]

SiC neutron detectors are an emerging technology which provides many advantages for monitoring harsh nuclear environments. SiC detectors can operate up to at least 700 °C and have been shown to withstand high doses of gamma-rays, neutrons and charged particles. Additionally, measurements have shown that irradiation of SiC at high temperatures reduces the radiation damage effects of the irradiation.

More elevated-temperature data are needed to understand the effects of temperature on mitigation of radiation damage in SiC. These effects are much more dramatic than those observed from post-irradiation annealing [55], and their understanding is crucially important for evaluating the applicability of SiC detectors in high-temperature, high-fluence nuclear environments.

It has been hypothesized [7] that so-called self-annealing operation may be possible with SiC detectors. If the rate of mitigation of radiation-induced damage at an elevated temperature is greater than or equal to the rate of introduction of radiation-induced damage, the effects of radiation should not limit the lifetimes of SiC detectors in that environment. Although an intriguing possibility, it remains to be demonstrated.

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