PROPERTIES OF SIC SEMICONDUCTOR DETECTOR OF FAST NEUTRONS INVESTIGATED USING MCNPX CODE

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1. Introduction

The potential of Silicon Carbide (SiC) for use in semiconductor nuclear radiation detectors has been long recognized. The wide bandgap of SiC (3.25 eV for 4H-SiC polytype) compared to that for more conventionally used semiconductors, such as silicon (1.12 eV) and germanium (0.67 eV), makes SiC an attractive semiconductor for use in high dose rate and high ionization nuclear environments. SiC is also attractive because it can operate stably at elevated temperature (up to 700°C [1]) and in environments with changing temperature profiles [2]. SiC detectors have now been demonstrated for high-resolution α- particle and X-ray energy spectrometry, β-ray detection, gamma-ray detection, thermal- and fast-neutron detection, and fast-neutron energy spectrometry [1]. Because of high temperature- and radiation-resistance, SiC neutron detectors are ideally suited for nuclear reactor monitoring applications, for monitoring of neutron exposures in boron-capture neutron therapy, for monitoring of spent nuclear fuel, etc.

The present work focused on the simulation of particle transport in SiC detectors of fast neutrons using statistical analysis of Monte Carlo radiation transport code MCNPX [3]. Its possibilities in detector design and optimization are presented.

2. Silicon Carbide Fast Neutron Detectors

Detection of fast neutrons in SiC detectors is based on the observation of charged-particle products of neutron-induced reactions with silicon and carbon nuclides in the active volume of the detector as demonstrated in Fig. 1. Fast neutrons with energy range from 100 keV to several tens of MeV are detected indirectly through elastic scattering and through other nuclear reactions with the Si and C atoms leading to the creation of ionizing particles within or close to the detector active volume which carry part of the kinetic information of the incoming neutron. Generally, neutron elastic scattering is possible with neutrons of all energies, but other reactions may occur

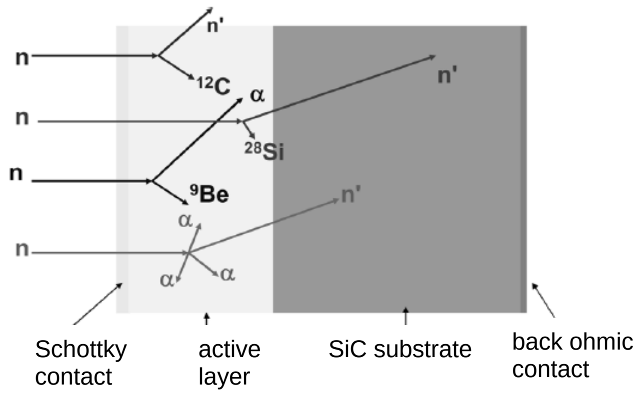

Fig.1. *Schematic representation of fast neutron reactions with Si and C nuclides in SiC detector [2].*

depending on the neutron energy and reaction energy threshold. The most prominent are $^{12}C(n,\alpha)^{9}Be$ and $^{28}Si(n,\alpha)^{25}Mg$ reactions. The fast-neutron induced reactions and the respective reaction energy thresholds are listed in Tab.1.

Tab.1. *Fast neutron reactions in SiC and the respective energy thresholds [1].*

Reaction	Neutron Energy Threshold (MeV)
$^{28}Si(n,n')^{28}Si$	0
$^{28}Si(n,n')^{28*}Si$ (first excited state)	1.843
$^{28}Si(n,\alpha)^{25}Mg$	2.749
$^{28}Si(n,p)^{28}Al$	3.999
$^{12}C(n,n')^{12}C$	0
$^{12}C(n,n')^{12*}C$ (first excited state)	4.809
$^{12}C(n,n')^{12*}C$ (second excited state)	8.292
$^{12}C(n,n')^{12*}C$ (third excited state)	11.158
$^{12}C(n,n')^{12*}C$ (fourth excited state)	13.769
$^{12}C(n,\alpha)^{9}Be$	6.180
$^{12}C(n,n')3\alpha$	7.886
$^{12}C(n,p)^{12}B$	13.643

Although the bare SiC material is able to register fast neutrons straightly, it was demonstrated that its detection efficiency can be enlarged if covered by an appropriate conversion layer [4]. The most common material used as converter for fast neutrons is high density polyethylene (HDPE) because of high concentration of hydrogen. Due to the similarity between the neutron and hydrogen nucleus, the energy transfer from the neutron to the hydrogen is favored. Secondary generated protons emitted as a result of neutron interaction in conversion layer carry information about neutrons and can be directly detected with a charged particle detector.

3. MCNPX radiation transport code

In order to design a good neutron detector with satisfying detection efficiency it is necessary to understand the transport properties of constituent materials properly. Monte Carlo computer codes proved very useful in detector design because they enable device characteristics and performance to be predicted prior to fabrication. MCNPX code used in our study is the result of a merger of MCNP with LAHET (Los Alamos High-Energy Transport) and is under continuous development. The version of the code MCNPX 2.7.0 released in April 2011 enables seamless transport of 34-particle types (including 4 light ions) and 2000+ heavy ions at nearly all energies by mixing and matching of nuclear data tables and model physics. It comprises an extension of neutron model physics below 20 MeV and of particular interest in the field of detector design is the ability to produce and track charged particles created by elastic recoil from neutrons or by other nuclear reaction. In this way, the secondary particles can be banked for subsequent transport.

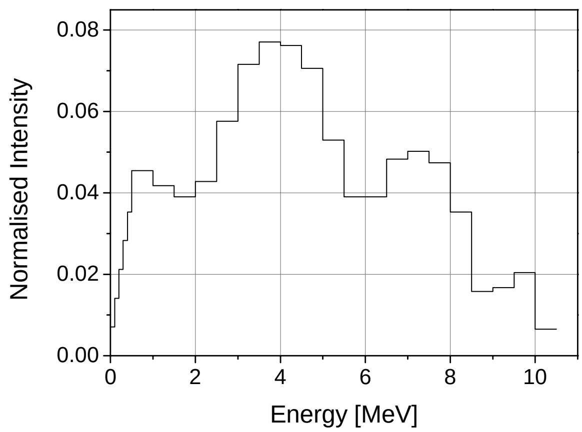

Fig.2. *The neutron spectrum from the ^{239}Pu-Be source used in MCNPX simulation.*

MCNPX modelling of the fast-neutron response of SiC detector was carried out for fast neutrons produced by ^{239}Pu-Be source with the mean energy of about 4.3 MeV. The source has been modeled as a point source collimated into a cone with differential flux distribution depicted in Fig. 2. The simulations have been carried out for a bare SiC detector and for a detector with conversion layer composed of HDPE. The converter layer was juxtaposed in front of the detector. Its thickness was chosen according to the results from the calculations performed in [5], where the optimal thickness of HDPE conversion film yielding the best efficiency of neutrons to protons conversion was determined to be 500 μm.

4. Results

In the simulations, the thickness of the SiC material representing detector active volume varied from 5 to 1500 μm. For each thickness, the following quantities were calculated: flux density of protons, alpha particles and heavy (recoiled) ions (h.i.), reaction rate of elastic scattering on Si and C atoms, (n,α), (n,p) and (n,n') reactions, total proton production, total alpha particle production, production of residual nuclei and energy deposited by protons, alpha particles and heavy ions. The same quantities have been determined for SiC detector with 500 μm thick HDPE conversion film.

According to the calculated reaction rates, the incident neutrons transfer part of their energy mostly via elastic scattering on Si and C atoms. From the values of reaction rates and incoming neutron flux density, the maximal theoretical detection efficiency has been assessed to be about 0.18 % for 100 μm thick active layer. This value is increasing with increasing thickness of the detector active volume.

The interaction of high-energy neutrons with target nuclei causes production of many residual nuclei, which were recorded to an F8 tally used with an FT8 RES special treatment options. The following nuclides have been created: ^{9}Be, ^{10}Be, ^{12}C, ^{25}Mg, ^{26}Mg, ^{27}Mg, ^{28}Al, ^{29}Al, ^{30}Al, ^{28}Si, ^{29}Si and ^{30}Si. All these nuclides arise as products of reactions listed in Tab. 1 and can produce ionization in the active layer of SiC detector.

In Fig. 3, the flux density of alpha particles, protons and heavy ions is depicted as a function of the detector active volume thickness. The shape of the curves can be explained by the finite and energy dependent range of the charged particles, which are additionally distributed in energy. E.g., the range of 4 MeV-protons, α-particles, C and Si ions in SiC are about 101 μm, 11.7 μm, 2.74 μm and 1.78 μm, respectively. Hence, many of the protons, α-particles and recoil ions that are produced by incoming neutrons have ranges in SiC that can be greater than the active region thickness and will deposit a variable amount of energy.

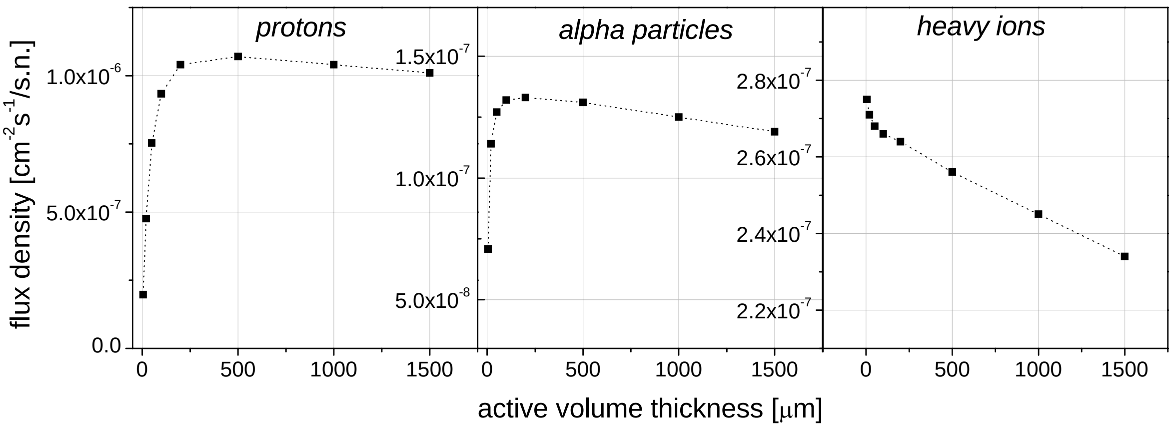

Fig. 3. *Flux density of alpha particles, protons and heavy ions depicted as a function of the detector active volume thickness.*

The calculated energy deposition by secondary charged particles from neutron interactions (p, α and h.i.) and evaluated individual contributions from protons, α-particles and recoil ions to the whole deposited energy are depicted in Fig. 4 and 5. The calculated energy deposition is considerably enlarged if conversion layer is added to the detector (Fig. 5). In this case, the recoiled protons represent the dominant contributor to the whole energy deposited, unlike in case of the bare SiC detector, where the recoil ions transfer the biggest part of the whole energy deposited by the charged particles.

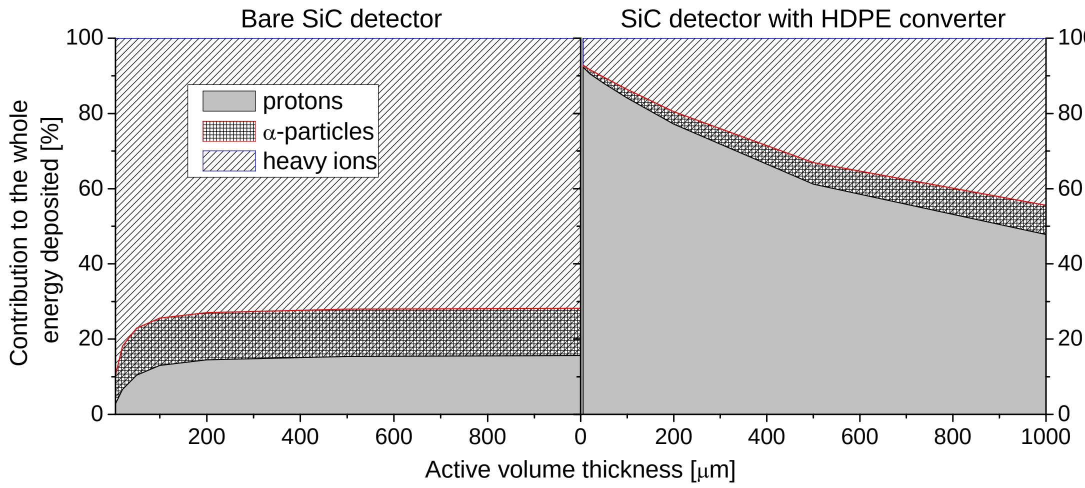

Fig.4. *Contributions from secondary particles (protons, α-particles and recoil ^{28}Si and ^{12}C atoms) to the whole deposited energy as a function of the detector active volume thickness (detector without and with 500 μm thick HDPE conversion film).*

5. Conclusion

It was shown that MCNPX code proved as very advantageous self-contained simulation program for fast neutron and secondary particle tracking. The main mechanisms of fast neutron interactions in SiC detector material have been quantified and the contributions from secondary particles (protons, alpha particles and recoil atoms) to the whole deposited energy have been calculated. It was demonstrated that detector sensitivity to fast neutrons can be enhanced when an appropriate conversion layer is added.

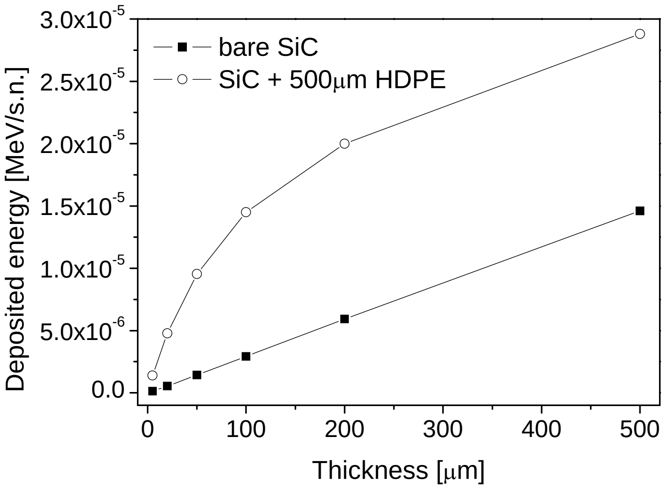

Fig.5. *Energy deposited by charged particles in SiC detector active volume.*

Acknowledgement

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