Materials Science Forum
ISSN: 1662-9752, Vol. 1062, pp 509-513
doi:10.4028/p-7027g3

Submitted: 2021-10-14
Revised: 2022-02-20
Accepted: 2022-03-17
Online: 2022-05-31

Neutron Detection Study Through Simulations with Fluka

A.Muoio[1,2,a*], A. Meli[1,3,b], A. Trotta[4,c], M. Parisi[4,d], L. Meda[5,e] and F. La Via[1,2,f]

[1]CNR-IMM, VIII Strada 5, 95121 Catania, Italy

[2]INFN - LNS, Via S. Sofia 62, 95123 Catania, Italy

[3]Università di Catania Dipartimento di Fisica via S.Sofia 64,95123 Catania , Italy

[4]ENI-MAFE, Via A. Pacinotti 4, 30175, Venezia, Italy

[5]ENI - Renewable Energy, Magnetic Fusion and Material Science Research Center, Via G. Fauser 4, 28100 Novara, Italy

*Corresponding author email: [a]annamaria.muoio@imm.cnr.it, [b]alessandro.meli@imm.cnr.it, [c]antonio.trotta@eni.com, [d]miriam.parisi@eni.com, [e]laura.meda@eni.com, [f]francesco.lavia@imm.cnr.it

Keywords: fluka, neutron detection, silicon carbide

Abstract. In this work the purpose of the simulations is to optimize a new large volume Silicon Carbide (SiC) detector for 14.1 MeV neutrons. The device has an active thickness obtained by epitaxial growth and an active area of 25 mm^2. In the first step of the simulations we compare SiC detector performance to Diamond and Silicon detectors, with the same geometric features. In the second step of the simulations we have found the best solution to improve the response of the detector for a fixed epitaxial layer thickness using an overlayer of aniline (C_6H_7N).

Introduction

In theoretical and experimental studies of nuclear physics, an important role has always been played by the interaction of neutron beams with matter; in fact, by being electrically neutral, they are able to overcome the Coulomb barrier and interact directly with the target's nuclei. They are fundamental for investigating the structure of matter and nuclear reactions. Silicon Carbide (SiC) is a compound semiconductor, which is considered as a possible alternative to silicon for particles and photon detection. Its characteristics make it very promising for the next generation of nuclear and particle physics experiments where the temperature and the radiation environment preclude the use of conventional silicon detectors [1-2]. Some studies, based on the effects of neutron, proton and heavy ions irradiation on SiC diodes, evidenced the high radiation hardness of these devices [3], that maintain their performance after high dose irradiation [4]. In this study the efficiency in the detection of neutrons for different materials and thickness is studied by Fluka Montecarlo simulations for a neutron Energy of 14.1 MeV and a fluence of 4.45 10^{11} (n/cm^2). In previous studies it has been observed that several materials can improve the efficiency of the neutron detectors [5] but these materials cannot be implemented during the detector realization process. Then we have decided to use an aniline (C_6H_7N) overlayer that can be easily deposited during the detector realization process and that can further improve the detector efficiency, for a fixed epitaxial layer thickness.

Results and Discussions

Reactions with fast neutrons are widely used in nuclear sciences. Investigation of the mechanism of their reactions could improve knowledge on atomic nuclei structure. The following Table 1 shows the possible reactions for fast neutrons with Energy= 14.1 MeV on a SiC detector [6].

Table 1 Fast Neutron-Induced Reactions in Silicon Carbide

Reaction	Q Value (MeV)	Energy Threshold (MeV)
$^{12}C(n,n')^{12}C$ ground state	0	0
$^{12}C(n,n')^{12}C$ 2+	-4.4389	4.8088
$^{12}C(n,\alpha)^{9}Be$	-5.7012	6.4196
$^{12}C(n,n')3\alpha$	-7.3666	8.4286
$^{12}C(n,p)^{12}B$	-12.5865	13.7401
$^{28}Si(n,n')^{28}Si$ ground state	0	0
$^{28}Si(n,n')^{28}Si$ 2+	-1.7790	1.8425
$^{28}Si(n,\alpha)^{25}Mg$	-2.6537	2.7653
$^{28}Si(n,p)^{28}Al$	-3.8599	4.0042

The investigations through simulations were carried out with the Monte Carlo software Fluka [7]. A parallelepipedal telescopic detector with a base surface of 25 mm^2 was simulated. In the first study of simulations the SiC interactions with neutrons has been studied and compared with Silicon and Diamond detectors, with the same geometric features. From these simulations reported in Fig. 1a it is possible to observe that the interacting neutrons are much higher in Diamonds with respect to SiC and Silicon because the scattering cross section of carbon is higher than that one of silicon. After that the active area of the SiC detector was increased and with this doble area the interacting neutrons are comparable between the diamond and the SiC detectors. This result is extremely interesting because the better material quality of the SiC material with respect to diamond can give the opportunity to obtain larger devices and then a comparable or better efficiency. Of course, the area of the detector cannot be increased over a certain value because the increase of the area also produces a considerable decrease of the detector production yield, with a subsequent increase of the detector costs.

The second step of the simulations is to study another approach to improve the sensitivity of silicon carbide detectors; from previous studies [8-9], it has been observed that aniline is a good activator of nuclear reactions with fast neutrons. The simulations are done with two detector layers, with the first stage consisting of aniline (C_6H_7N) and a second one of silicon carbide (SiC – 4H). Different thickness combinations of the first stage were analyzed while SiC layer has a fixed thickness of 250 µm. The characteristics of the incident neutron beam were the same of the previous simulations set: Neutrons energy 14.1 MeV and Neutrons fluence equal to 4.45 x 10^{11} neutrons/cm^2. Among the possible reactions induced by the neutron-carbon interaction, there are multiple interactions of elastic and inelastic scattering and reactions of the type (n, α) and (n, p); a particular analysis was undertaken for the study of proton elastic interactions, for different layers of aniline relating to the bulk of SiC (thickness=250µm) Fig 1b.

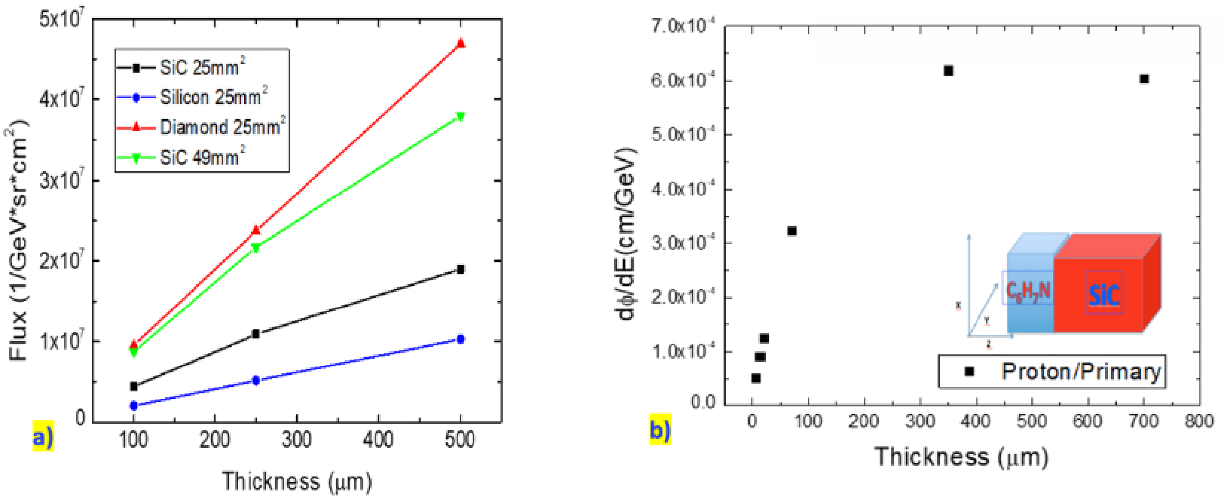

Fig.1a Flux versus thickness for different materials (Diamond, Silicon and Silicon Carbide) at different thickness (100, 250 and 500 µm) Fig.1b Differential protons Flux versus thickness of aniline (7, 14, 21, 70, 350 e 700 µm), for the two layers detector Aniline + SiC.

From these simulations it is possible to observe that the maximum thickness of the aniline stage should be 250 µm, so as to increase the flux of protons in the SiC detectors. Higher thickness produces a saturation because the protons generated at the surface cannot go out from the aniline layer and reach the silicon carbide.

In all the materials, as reported in Fig. 1a, the interacting neutrons increase by increasing the thickness of the detectors, but very thick detectors are difficult to be realized due to the increase of defects density in very thick epitaxial layers [10-11]. Furthermore, a higher bias is needed to deplete the thick epitaxial layer as shown in Fig.2a. To decrease this high voltage it is possible to decrease the doping concentration in the epitaxial layer, but, in the case of silicon carbide is extremely difficult to reach doping concentration lower than $1x10^{14}/cm^3$.

Another aspect that should be taken under consideration is that when we use very thick epitaxial layers for the detectors, we need to have a diffusion length larger than the depleted layer to have a good charge collection. From Fig.2b it is possible to observe the diffusion length data, calculated using time resolved photoluminescence (TRPL) for the lifetime calculation. The diffusion length values are higher than the epi-layer thickness for our samples [12] with an optimized epitaxial process, while in the case of other epitaxial growth processes, the diffusion length is close to thickness of the epitaxial layer or even lower. Then with a good epitaxial process the diffusion length does not seems to be the limiting factor in the increase of the epitaxial layer thickness and of the neutron sensitivity. Instead, the high voltage necessary to deplete a thick epitaxial layer, and the low yield of the very thick detectors with large area are the main limitation of this technology. For this reason, the implementation of the overlayer of aniline can be a possible route for the increase of the detector efficiency.

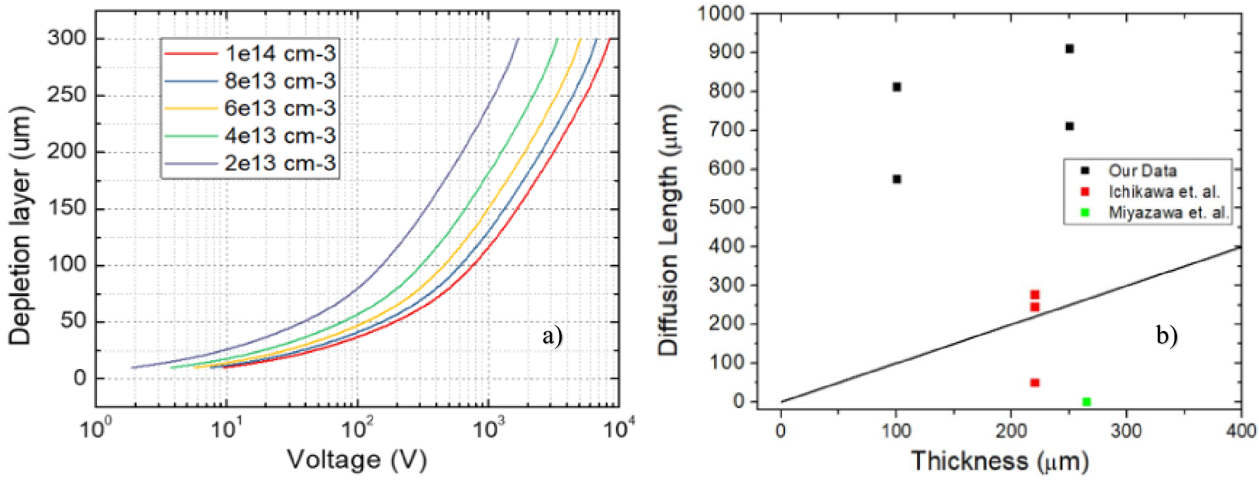

Fig.2a Voltage necessary to obtain a depletion over the entire epitaxial layer as a function of the thickness of the layer with different carrier concentration.Fig.2b Diffusion length as a function of the thickness for our data compared with data in literature [13-14].

Conclusions

Silicon carbide (SiC) is used extensively for the production of high-power semiconductor devices. Today the use of this material in radiation environments such as fusion reactors creates excitement in the nuclear physicist.. In this study we have used FLUKA simulation code to investigate radiation induced effects in 4H-SiC for neutrons of 14 MeV. With this work we have observed that we need very thick epitaxial layers to have good sensitivity of the SiC detector at this high energy. For the same thickness of the detector the silicon carbide one is less sensitive with respect to the state of the art diamond detectors, but increasing the area, thanks to the superior quality of this material, it is possible to obtain similar sensitivity. The main difficulties for the realization of very thick detectors is related to the high voltage needed to depleted the thick layers and to the yield decrease due to the large area and the high epitaxial layer. The use of an overlayer of aniline can produce, according to our simulations, a considerable increase of the detector sensitivity.

References

[1] A. Owens and A. Peacock, Nucl. Instrum. Methods A, 531, 18 (2004).

[2] E. V. Kalinina et al., Phys lett., 34, 210 (2008).

[3] A. Muoio et al., EPJ Web of Conferences, 117, 10006 (2016).

[4] S. Tudisco et al., EuNPC 2018 Conference, 42 C, 74 (2019).

[5] F.H.Ruddy et al., Proceedings of the 13th International Symposium, doi: 10.1142/9789814271110_0014, (2009)

[6] F.H. Ruddy et al., IEEE Transactions on Nuclear Science 53(3):1666 – 1670 (2006).

[7] http://www.fluka.org/fluka.php.

[8] T. L. Johnson et al.,Proceedings of the America nuclear Society on Theory and Pratices in Radiation Protection and Shieding, ISBN 0-89448-132-0, (1987).

[9].C.H.Lee et al., Nuclear Engineering and Technology Volume 49, Issue 3, 592-597, https://doi.org/10.1016/j.net.2016.10.001, (2017)

[10] F. La Via, M. Camarda, A. La Magna, Applied Physics Reviews 1, 031301 (2014)

[11] F. La Via, G. Izzo, M. Camarda, G. Abbondanza, and D. Crippa, Materials Science Forum Vols. 615-617, 55 (2009).

[12] A. Meli, A. Muoio, A. Trotta, L. Meda, M. Parisi and F. La Via. Materials, 14, 976 (2021).

[13] S. Ichikawa et al. Applied Physics Express 5, 101301 (2012).

[14] T. Miyazawa et al. Applied Physics Letters 97, 202106 (2010).