

250 μm Thick Detectors for Neutron Detection: Design, Electrical Characteristics, and Detector Performances

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Abstract. Solid State Detectors (SSD) are crucial for fast neutron detection and spectroscopy in tokamaks due to their solid structure, neutron-gamma discrimination, and magnetic field resistance. They provide high energy resolutions without external conversion stages, enabling compact array installations in the harsh environment of a tokamak. Research comparing diamond and 4H-SiC detectors highlights thickness as a key efficiency factor. A 250 μm SiC epilayer with low doping, grown using a high-growth-rate process, exhibits sharp interfaces and minimal defects, essential for neutron detectors. The study evaluates detector designs, and performance using a 4H-SiC substrate. Various detector designs, such as Schottky diodes and p/n diodes, are assessed via I-V and C-V measurements, addressing high depletion voltage challenges. Preliminary neutron irradiation tests validate detector functionality, energy resolution and confirming detector reliability.

Introduction

Solid State Detectors (SSD) are object of interest in the field of fast neutron detection and spectroscopy in tokamaks [1]. Their solid structure, ability to discriminate neutrons from gamma radiation [2] and insensitivity to magnetic field makes them prime candidates for neutron detection close to the plasma [3]. Furthermore, the fact that their detection mechanism does not rely on a conversion stage outside the active volume allows for very high energy resolutions. In perspective, their small dimensions also allow for their installation in arrays enabling the survey of the tokamak volume along multiple lines of sight [4]. There are also solid prospects for the functionality of SiC in harsh environments (such as high temperature [5,6] or high radiation [7,8]) such as the one encountered inside the breeding blanket (or, in general, close to the plasma). Nowadays, the best detectors used in this field are diamond-based, single-crystal diamond (SCD), with important

performances, but the production capability of large-area wafers and the lower cost, with respect to the diamond, allow the use of SiC material.

In a previous paper, the comparison between diamond and 4H SiC detectors with thicknesses of 100 micron was performed [9]. It has been noted that the efficiency of diamond detectors increases with increasing thickness because the probability of an interaction between the neutrons and the diamond substrate increases considerably. Then, also in the case of SiC, it is necessary to increase the thickness of the SiC layer to increase the efficiency of the detector. This can be done by using semi-insulating substrates that are 500 microns thick, or by trying to increase the thickness of the epitaxy. The first approach has been used in the past, but the performance of the detector was limited by the high defect densities of this material and its low carrier lifetime that reduce its charge collection [10]. Furthermore, this approach also shows some polarization effect and instability at high temperatures. For this reason, a 250 μm epilayer was grown with a high growth rate process and a low doping level. In previous papers, the epitaxial growth mechanism of this process using TCS (trichlorosilane) was described [11,12] and showed that it is possible to obtain very low doping levels, sharp interfaces, a low-density point, and extended defects. All these properties are important for neutron detectors. In fact, the low doping concentration is fundamental to using a lower depletion voltage for a thick detector. The low point defect density produces a large carrier diffusion length and then a good charge collection efficiency of a detector, while the low density of extended defects generates a high yield of the large-area detectors. In fact, by a previous paper it has been observed, through simulation with the FLUKA tool [13], that both thickness and area are important to increment a detector's efficiency. In this work, both the different design of the detectors and the detectors performances have been evaluated. Different detector designs, including Schottky diodes and p/n diodes, are assessed using I-V and C-V measurements. Challenges related to high depletion voltage are discussed. Preliminary neutron irradiation tests confirm detector functionality, energy resolution, and stability.

Experiment

A 4H-SiC substrate, characterized as n-type with a silicon face and a slight off-axis orientation of 4° , served as the substrate for an epitaxial layer of 250 μm in thickness, which was meticulously grown using the chemical vapor deposition technique within a horizontal hot-wall reactor (LPE PE106). A complete characterization of this material is reported in [14]. On this material two different detector designs have been realized. The first one was a simple Schottky diode with a field plate edge structure while the second one was a p/n diode with a 250 μm Junction Termination Edge (JTE) structure. A schematic of the two detectors is reported in Fig. 1.

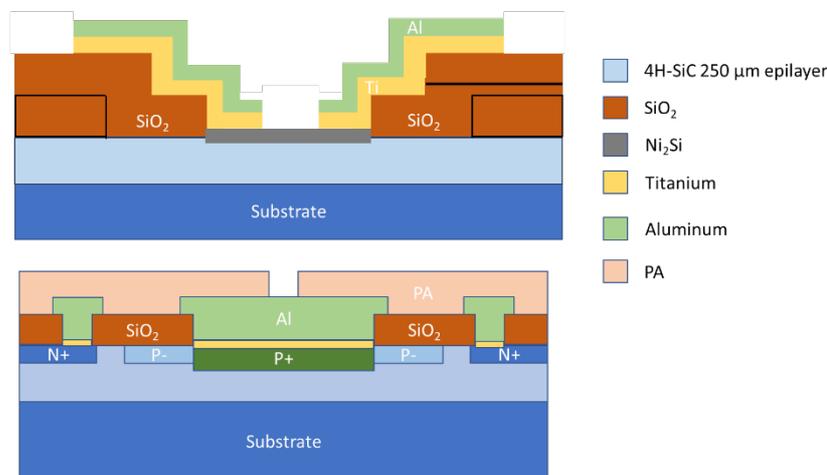


Fig. 1. Schematic of the Schottky and p/n junction diodes on a 4H-SiC substrate.

Results

The detectors were tested by I-V and C-V measurements, with bias up to 1000 V. Compared to the Schottky barrier diode (SBD), the pn structure, of the same $2.5 \times 2.5 \text{ mm}^2$ area, has a larger turn-on voltage in forward bias (Fig. 2(a)) and a better leakage current (Fig. 2(b)) with current density values lower than $10^{-10} \text{ A cm}^{-2}$ at more than 600 V. In the case of the Schottky diode it is possible to observe a high leakage current due to the lower barrier height, the Schottky effect and low quality of the edge structure with the field plate. The expected ideality factors n , usually 1 for the SBD and 2 for the pn diodes, were extracted from the slope of the linear fit of I-V curves showed in Fig. 2 (a), while the barrier heights of the diodes ϕ_b were obtained through the thermoionic current-voltage relation at $V=0$.

In both cases, the C-V measurements (Fig. 3) show a doping of the epitaxial layer of about $6-8 \times 10^{13}/\text{cm}^3$ for the pn diodes and of about $10^{14}/\text{cm}^3$ for the Schottky diodes. With these doping concentrations, the depletion voltage is higher than 5 kV. This represents a significant issue for the detector electronics and for the preamplifier that generally work at a maximum voltage of 1 kV. Thus, a considerable reduction of the doping level to $1-2 \times 10^{13}/\text{cm}^3$ should be reached in the future to obtain a depletion layer of 250 μm with less than 1 kV applied bias.

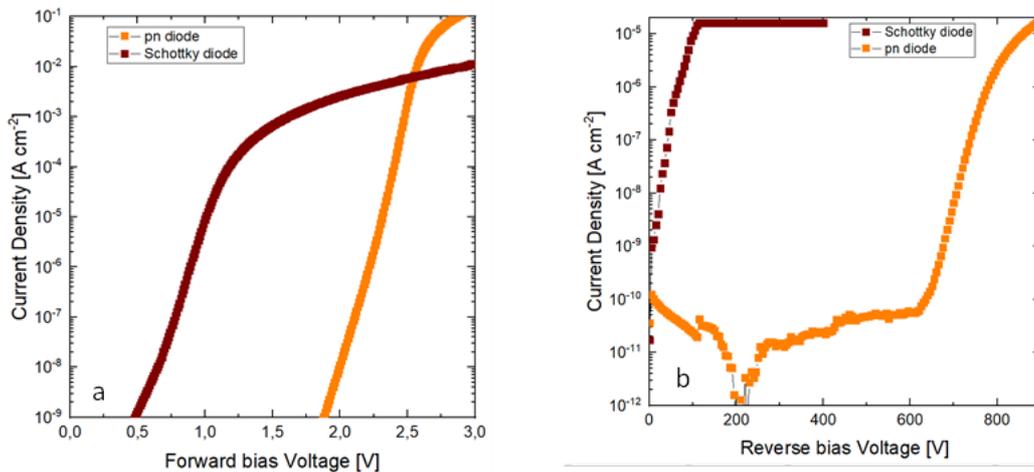


Fig. 2. I-V characteristic in forward (a) and reverse (b) bias of the two different types of detectors.

The curvature of the $1/C^2$ vs. voltage characteristics at high voltage is due to the leakage of the junctions that is especially high in the Schottky diode case. The value of ϕ_b for the p/n diode was used to estimate the doping concentration of the p^+ -doped side of the junction after the C-V measurement. In fact, using the relation $N_a = \frac{n_i^2}{N_d} \exp\left(\frac{qV_{bi}}{kT}\right)$, It is possible to obtain a value of N_a of $1.2 \times 10^{19}/\text{cm}^3$, that is close to the peak value of the implanted junction. The donor density N_d and built-in potential V_{bi} are extracted from C-V measurements, and the latter one is related to the barrier height previously measured with I-V technique through the relation $\Phi_B = V_{bi} + V_0$, with $V_0 = \frac{kT}{q} \ln\left(\frac{N_c}{N_d}\right)$, which is around 0.30 V, using the N_d value extracted from the same measurement. If the difference of the two potentials overcome the value of V_0 , it could be due to non-uniformity of the Schottky barrier or variation in doping of the p/n junction.

In the case of the Schottky device it is possible to observe that the barrier height obtained from the I-V forward characteristic reported in Fig. 2(a) is of 1.35 eV, while that one obtained from the C-V characteristic reported in Fig. 3 is 1.58 eV. This is consistent with the high value of the ideality factor and with the Tung model [15]. In a similar paper [16] it has been observed that the Schottky barrier height and the ideality factor increases at high epitaxial thickness and the reported value are in good agreement with our data. Even in the case of the p/n diode a large difference between the barrier height obtained from the I-V characteristics and that one obtained from the C-V measurement has been observed. A comparison of the electrical characteristics of the diodes studied in this work with

other SiC devices with similar epilayer thickness is presented in **Table 1**. Schottky diodes technology seems to be well consolidated, considering the large area of the devices obtained in various works, while, for pn junction diodes most of the devices do not approach thicknesses of hundreds of microns. From this comparison, it is clear that the V_{bi} seems to be independent by the thickness of the epitaxial layer, but it depends mainly the doping levels of the layers. The leakage current density at 100 V in reverse bias is presented, showing a very low value for the pn junction diode discussed in this work, compared to the others, that is related to the high quality of the thick epitaxial layer.

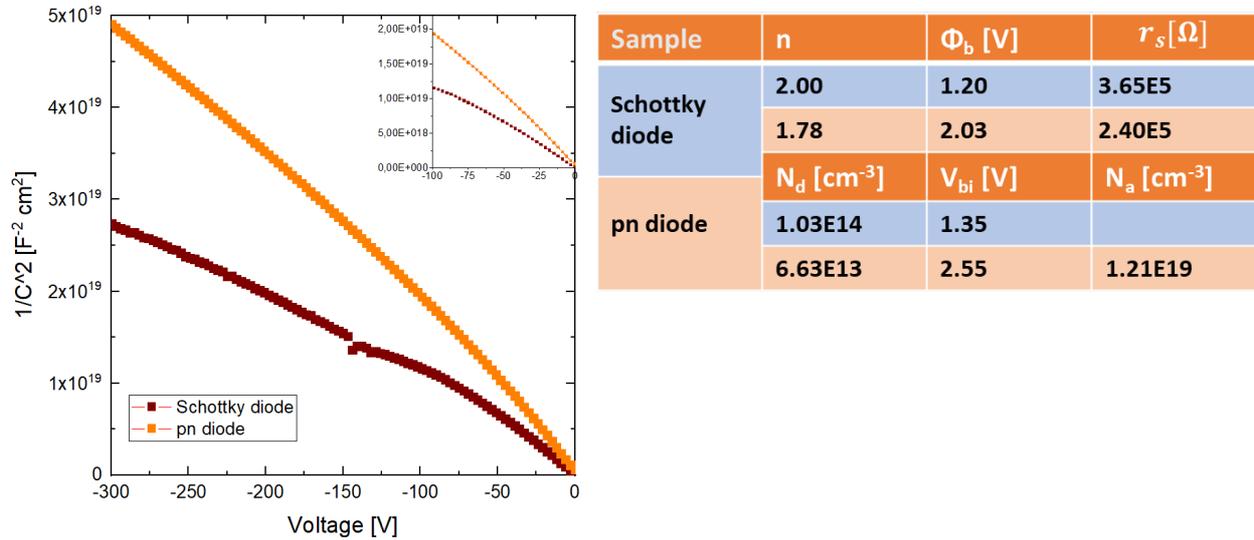


Fig. 3. C-V characteristic in reverse bias of the two different for the Schottky and the pn junction diodes, with a close-up on the lower bias region. It is evident the difference in slope for the two curves. On the right, are reported the ideality factor n , the barrier height ϕ_b , the series resistance r_s , the donor density N_d of the epilayer, the built-in potential V_{bi} and the acceptor density N_a of the p^+ -doped layer.

Table 1. Comparison of the devices presented in this work against other Schottky and pn junction diodes. The 250 μm epilayer Schottky device presented in [16] is tested in a range of temperatures from 350K to 600K, while the pn junctions in [17-18] at room temperature.

Sample	Epi-thickness [μm]	Area [mm^2]	V_{bi} [V]	N_d [cm^{-3}]	Leakage current density at 100 V [A/cm^2]
Schottky diode (this work)	250	2.50x2.50	1.35	1.03×10^{14}	9.18×10^{-6}
Schottky diode [16]	250	8.00x8.00	1.50-2.10	1.00×10^{14}	$\sim 1.00 \times 10^{-10}$
p/n junction (this work)	250	2.50x2.50	2.55	6.63×10^{13}	2.37×10^{-11}
p/n junction [17]	268	0.20	2.75-2.80	$1-2 \times 10^{14}$	$< 1.00 \times 10^{-4}$
p/n junction [18]	186	0.07	~ 3.00	2.30×10^{14}	$\sim 9.00 \times 10^{-6}$

A preliminary DT-neutron (14 MeV) irradiation was performed on both the SiC Schottky diode and pn junction diode to test their functionality as neutron detectors [19, 20]. The devices have been tested under different conditions, with a bias up to 150 V for the Schottky devices, and with a temperature ramp for the p/n diodes. The resolutions of these devices are comparable, even with a slightly different setup. In Fig. 4, the deposited energy vs the occurrence of the neutron detection is reported, with a gaussian fit realized with these data. The results obtained for p/n junctions probably underestimate the number of occurrences due to the presence of a mineral cable in the setup and a pressure contact

on the devices, but still the signal is optimal compared to the one associated to Schottky devices, even if with a larger FWHM.

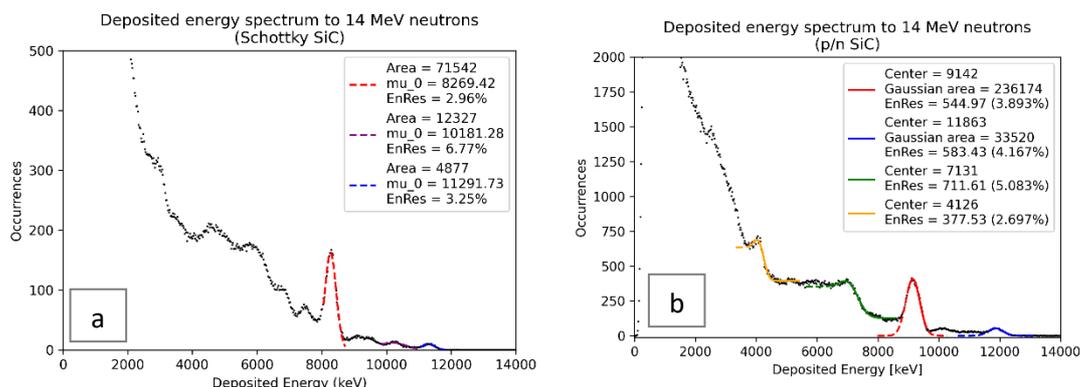


Fig. 4. Deposited energy vs occurrence of DT-neutron (14 MeV) detection for (a) SiC Schottky junction with a 150 V bias applied, and (b) pn diode devices at room temperature.

Conclusion

SiC possesses remarkable attributes, including a wide bandgap, excellent electrical properties, and resistance to radiation, making it exceptionally well-suited for demanding environments. The primary aim is to monitor the plasma confined within the core of a tokamak reactor used for nuclear fusion reactions. The devices developed in Catania have a unique characteristic: a high-quality epitaxial layer of SiC, which is 250 μm thick and functions as the neutron detection region. Two types of devices have been crafted using this substantial layer: Schottky Barrier Diodes, representing the initial generation of detectors created in Catania, and p/n-junction diodes, representing the second generation. To achieve full depletion of the epitaxial layer with the actual doping level, it has been determined that a bias of 5000 V is necessary. The electrical characterization of these detector types revealed an impressive 10^{-11} A leakage current at 600 V for the p/n-junction diodes. This result is noteworthy, especially when compared to Schottky diodes, which typically exhibit low leakage current at voltages of less than 200 V.

These accomplishments were made possible through a thorough examination of the junction's edge structure. The detectors produced thus far show great promise in the realm of neutron detection, and a third generation of neutron detectors is planned to reach the full depletion of the 250 μm epitaxy with reverse bias lower than 1 kV and low reverse leakage current.

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