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A feasibility study of a SiC sandwich neutron spectrometer

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A B S T R A C T

The object of this work is the development of a semiconductor sandwich neutron spectrometer composed of a ^{6}LiF converter placed between two 4H–SiC Schottky diodes. In particular, the diodes construction, alpha detection characterization and preliminary neutron radiation damage tests are described, in order to evaluate the capability of the detector to work in harsh environments characterized by high neutron fluence rate. A theoretical determination of the optimal converter thickness and an analysis of the detection efficiency of the spectrometer at different neutron energies are performed with Monte Carlo simulations.

1. Introduction

Previous works have demonstrated that 4H–SiC Schottky diodes with a ^{6}LiF thin converter can be successfully used as neutron detector, exploiting the ^{6}Li(n,α) reaction which is characterized by a 4.78 MeV Q-value and a thermal cross section of 940 b (Lo Giudice et al., 2007). The signal produced by the neutron-induced reaction products can be easily discriminated from the gamma background on the basis of pulse height. The use of silicon carbide (SiC), a wide band gap (3.2 eV) semiconductor material with high thermal conductivity and breakdown electric field strength, as detecting material allows measurements in harsh environments characterized by high temperatures and intense neutrons and gamma radiation fields (Neudeck, 1995). These characteristics make SiC a candidate material for neutron detection and spectrometry when the use of the conventional silicon surface barrier detectors is not possible due to their radiation damage and high temperature resistance.

In this work the design of a SiC sandwich neutron spectrometer for harsh environments is described. To our knowledge, this represents the first attempt to construct a sandwich neutron spectrometer with a SiC semiconductor material. At first, the Schottky diode construction and characterization are reported. In a second step, the MCNPX code is used to evaluate the optimal converter thickness and to estimate the spectrometer detection efficiency.

2. Detector construction and characterization

The neutron spectrometer, based on the sandwich method, is composed of a thin ^{6}LiF (95% enriched in ^{6}Li) converter placed between two SiC Schottky diodes (Fig. 1a). The converter thickness was optimized with Monte Carlo simulations (Section 4). Neutrons are detected through alpha particles and tritons produced in the ^{6}Li(n,α) reaction, impinging on the depleted region of the diodes. Only the coincident pulses of the energy deposited in the two detectors by alpha and triton particles are registered and summed: after subtracting the Q-value from this signal, information about the energy of the incoming neutron can be obtained.

The first step was the fabrication and characterization of the Schottky diodes, whose section is shown schematically in Fig. 1b. The starting material was an n-type, 4H–SiC, 3 in wafer (from SiCrystal AG) made up of a top low-doped, n-type (3×10^{15} cm^{-3}), 20 μm thick epilayer, separated from the substrate (350 μm thick) by a high-doped, n-type ($>1 \times 10^{17}$ cm^{-3}), buffer layer 2 μm in thickness. The wafer micropipe density is less than 10 cm^{-2} (the micropipe density is the number of micropipes per cm^{-2}; each micropipe is basically a hollow core penetrating the entire wafer, see Kordina and Saddow, 2004). The fabrication procedure was applied to a 1 cm × 1 cm sample diced from the wafer and cleaned by means of a double step procedure: immersion for 5 min in a H_2SO_4:H_2O_2 (1:1) solution followed by a dipping in HF for 1 min. The ohmic contact, common to all diodes, consisted in a thin double-layer metal film of Ti and Ni (30 nm and 200 nm in thickness, respectively) deposited on the back side of the small die by

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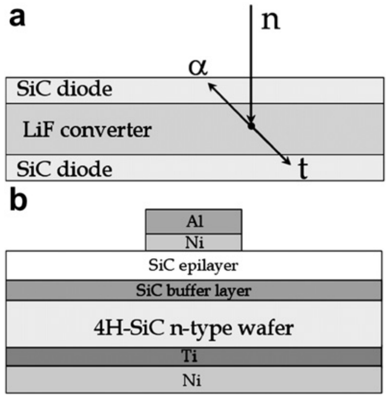

Fig. 1. a) Schematic representation of the sandwich neutron spectrometer (dimensions are not to scale). The ^{6}LiF reaction is considered (a thermal neutron incident on the spectrometer is represented in the scheme). b) Scheme of each Schottky diode which was realized on the 4H–SiC wafer (dimensions are not to scale).

means of electron beam evaporation. Subsequently, a rapid thermal annealing at 1000 °C for 5 min in N_2 atmosphere was performed. The Schottky contacts were obtained by evaporating a double-layer metal film of Ni and Al (100 nm and 500 nm in thickness, respectively). To avoid the dependence of the diode characteristics on the randomly distributed wafer defects, such as micropipes and stacking faults, a 5×5 matrix of diodes connected to a PCB board was defined (each diode will be identified in the matrix notation from now on). The matrix geometry has been defined by evaporating metals through a stencil mask. After the contact definition, the die was glued to a PCB board by means of silver paste and wedge bonding was used to connect diodes to the board pads. A photograph of the device at the end of the fabrication process is shown in Fig. 2. The central diode (a33) is 2.1 mm in diameter, while all the other diodes are 1.2 mm in diameter.

The diodes were electrically characterized by measuring both the *I–V* and the *C–V* operating curves (Piotto et al., in press). A wide dispersion of the forward and reverse *I–V* curves of the diodes was found. Four diodes were selected for the subsequent tests: the three diodes (a14, a15, a25) with the lowest reverse current density (less than 7.7×10^{-9} A cm^{-2} at 100 V) and the a33 diode. The latter has been chosen in order to verify the dependence of the response on the device area even if its reverse current density (1.6×10^{-6} A cm^{-2} at 100 V) was about two orders of magnitude higher. The possibility to connect in parallel these diodes in order to improve the active detector area was examined, as suggested by Dulloo et al. (1999): in this way a detector with a larger effective area can be obtained, by further reducing the leakage currents due to the randomly distributed wafer defects.

The radiation detection properties of the fabricated Schottky diodes were tested by irradiating them with alpha particles. The diodes were exposed in air at ambient pressure (26 mm source to detector distance) to a ^{239}Pu/^{241}Am/^{244}Cm source, emitting alpha particles of three main energies (5.157 MeV, 5.486 MeV and 5.804 MeV, respectively), by using a dedicated apparatus consisting in an aluminum enclosure of the source and detector in order to reduce the circuit noise (Piotto et al., in press). The alpha energy spectra of the considered source were acquired by means of an electronic chain composed of a preamplifier and a digital multichannel analyzer (which comprises the amplifier, the voltage supply system and the analog to digital converter). The results for the three diodes with the same sensitive area are shown in Fig. 3. The reverse bias voltage (200 V), applied via the preamplifier, determines a 9 μm thickness of the depletion layer, which is sufficient to stop completely all the alpha particles impinging on the detector, as calculated by simulating the irradiation geometry with the TRIM© code (Ziegler et al., 2008). Lower voltage determines a not complete detection of all the three alpha energy peaks.

The resulting intrinsic efficiency of the detectors for alpha particles was found in the interval 0.62–0.72, with the exception of the a33 diode which presents a poorer efficiency (0.34), most likely due to its higher content of defects because of its larger surface area. The a25 diode showed the best energy resolution (estimated as the full width at half maximum of the full energy peaks), which resulted to be 9% at 5.5 MeV (Fig. 3) for the ^{241}Am alpha energy peak (5.486 MeV emission energy, 3.3 MeV energy entering the diode after the 26 mm air gap). The 26 mm source to detector air gap was selected to place the Bragg peak of the alpha particles inside the Schottky diode depletion layer, so to maximize the detector intrinsic efficiency. For the adopted irradiation set up, the energy resolution is mostly affected by the energy straggling suffered by alpha particles in air and in the entrance window located upstream of the depleted region. This result is in accordance with other previous works (Ruddy et al., 1998), which used a collimated source, and the obtained resolution is acceptable for the realization of the neutron spectrometer.

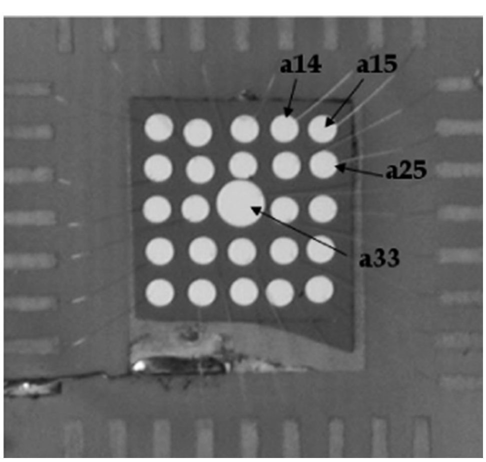

Fig. 2. Photograph of the 5×5 matrix of Schottky diodes (the four diodes with the lowest reverse current density are indicated).

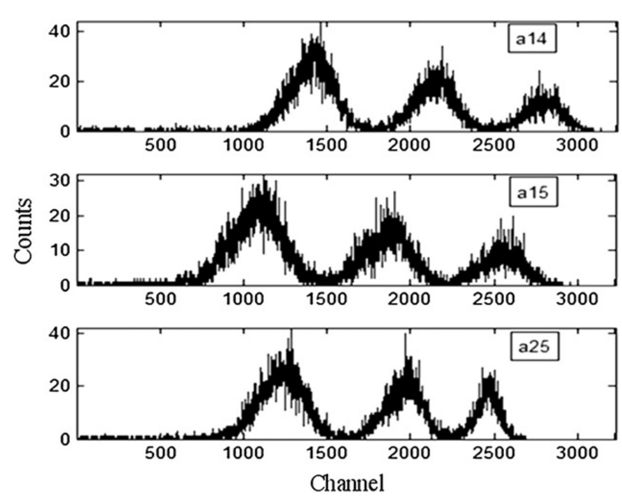

Fig. 3. Response of the selected SiC Schottky diodes with the same area (a14, a15 and a25) exposed in air to a mixed alpha source ^{239}Pu/^{241}Am/^{244}Cm. The number of registered counts for each channel is represented. The measurements are referred to a counting time of 14,400 s.