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Experimental characterization of semiconductor-based thermal neutron detectors

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ABSTRACT

In the framework of NESCOFI@BTF and NEURAPID projects, active thermal neutron detectors were manufactured by depositing appropriate thickness of ^{6}LiF on commercially available windowless p–i–n diodes. Detectors with different radiator thickness, ranging from 5 to 62 μm, were manufactured by evaporation-based deposition technique and exposed to known values of thermal neutron fluence in two thermal neutron facilities exhibiting different irradiation geometries. The following properties of the detector response were investigated and presented in this work: thickness dependence, impact of parasitic effects (photons and epithermal neutrons), linearity, isotropy, and radiation damage following exposure to large fluence (in the order of 10^{12} cm^{-2}).

1. Introduction

The projects NESCOFI@BTF (2011–2013) and NEURAPID (2014–2016, https://sites.google.com/site/csn5neurapid) [1,2], supported by the Scientific Commission 5 of INFN (Italy), extensively investigated the possibility of developing real-time neutron spectrometers able to simultaneously cover all energy components of neutron fields, from thermal up to GeV. The final users of these instruments will be neutron-producing facilities, ranging from medical to industrial and research fields. The leading is to resume the functionality of the Bonner Sphere Spectrometer into a single moderator embedding multiple active thermal neutron detectors, with the important result of determining the complete spectrometric information in a single exposure constitutes. The project proposed two different prototypal instruments [1], CYSP and SP^2, exhibiting unidirectional or isotropic response, respectively. These spectrometers embed respectively seven or thirty-one internal thermal neutron detectors, thus the availability of low-cost thermal neutron detectors with adequate sensitivity, miniaturization, linearity and reproducibility was one of the most important project targets. Commercially available thermal neutron detectors as ^{3}He or BF_3 counters were evaluated as basically unsuited, mainly due to the high cost. Diamonds covered with ^{6}LiF [3] would be potentially good candidates, since their thermal neutron response per unit area is in principle the same as ^{6}LiF-covered Silicon diodes. Nevertheless, mono-crystalline diamonds are usually expensive and not available in the large area format required by the project. Poly-crystalline diamonds can be realized with quite large active areas, but their cost per unit area was still too high compared with the budget constraints of the project.

Satisfactory results were achieved with “in-house” detectors, obtained by depositing appropriate thickness of ^{6}LiF powder on commercially available one cm^2 windowless p–i–n diodes, with 0.3 mm nominal depletion layer. These are called TNPD (thermal neutron pulse detectors). TNPDs with different radiator thickness, ranging from 5 to 62 mm, were manufactured by evaporation-based deposition technique.

A standard analog chain formed by a charge preamplifier and a shaper amplifier was used to amplify the signal from the detectors. Detectors were used un-biased. A commercial digitizer (NI USB 6366), operating in streaming mode under a customized software written in LabView, allowed acquiring the data on a laptop. The spectrum elaboration was performed according to the procedure described in Ref. [4]. The detectors were exposed to known values

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of thermal neutron fluence in two well-characterized thermal neutron facilities exhibiting different irradiation geometries:

- the ex-core radial column of the ENEA-Casaccia Triga reactor, exhibiting mono-directional distribution of the neutron fluence. The thermal beam normally impinged the detector surface. Different tests were performed, by operating the reactor at different power levels: 1, 10, 50 and 100 kW. The conventional thermal neutron fluence rate at the reference point in the thermal beam (hereafter called "thermal flux" to improve readability) was monitored every second through permanent monitor instruments (the so-called "linear amplifiers"). Accurate knowledge of the exposure time was possible through a pneumatic shutter, opening and closing the column in about one second. Previous measurements with gold foils made by TRIGA staff [5] allowed estimating in 1420 $cm^{-2}\,s^{-1}\,kW^{-1}$ ($\pm$5% one s.d.) the reactor power to thermal flux conversion coefficient.
- the INFN-LNF thermal cavity obtained by moderating an Am–Be source with a polyethylene cylinder, with nearly isotropic distribution of the neutron fluence. Here the thermal flux at the point of test is 1270 $cm^{-2}\,s^{-1}$ ($\pm$3% one s.d.) and the direction distribution of the field is roughly isotropic [6].

The following aspects were studied and presented in this work:

- Understanding the role of the radiator and of the semiconductor itself in the thermal neutron response and the effect of epithermal neutrons on the response. This was achieved by exposing bare and deposited detectors in absence or presence of a 1 mm thick Cd absorber;
- Determining the detector response, in terms of thermal neutron counts per unit fluence (cm^2), as a function of the radiator thickness;
- Response linearity;
- Response isotropy, evaluated by comparing the response in mono-directional and isotropic fields;
- Modification of the response following exposure to large thermal fluence (in the order of 10^{12} cm^{-2}), or radiation damage due to thermal neutrons.

2. Understanding the detector response

Being formed by a Silicon diode coupled to a ^{6}LiF radiator, the TNPD response to neutrons N, i.e. the pulse height distribution (PHD) of events interacting with the diode active volume, is generally given by superimposition of the following contributions:

$$N(V) = R_{th}(V) + R_{epi}(V) + S_{th}(V) + \gamma(V), \quad (1)$$

where V is the pulse height, $R_{th}(V)$ is the PHD due to thermal neutrons (below 0.4 eV) interacting in the radiator, $R_{epi}(V)$ is the PHD due to epi-thermal neutrons interacting in the radiator, $S_{th}(V)$ is the PHD due to thermal neutrons interacting in the Silicon substrate, where some minimal amount of Boron may be present. In principle also the epithermal contribution S_{epi} should be accounted, but its contribution is expected to be completely negligible, $\gamma(V)$ is the PHD due to secondary particles generated by photons accompanying the neutron field and interacting in the Silicon substrate.

The classical method to infer $R_{th}(V)$ is to expose the TNPD with and without a 1 mm thick Cd absorber in the form of a box covering the whole detector. However, this introduces a further term $\gamma_{Cd}(V)$, i.e. the PHD due to prompt photons coming from the neutron capture in the Cadmium filter. To investigate these aspects, additional exposures were performed with a non-deposited detector (bare) with and without the 1 mm thick Cd box. The PHDs obtained in the four cases are described by Eq. (1)

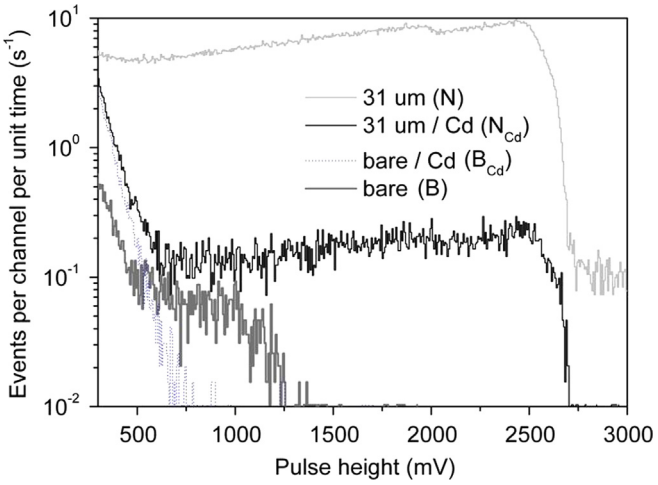

Fig. 1. Pulse height distributions for the 31 μm TNPD and the bare detector exposed with and without the Cd box at 50 kW. Data are normalized to the unit time. Channel width = 3 mV.

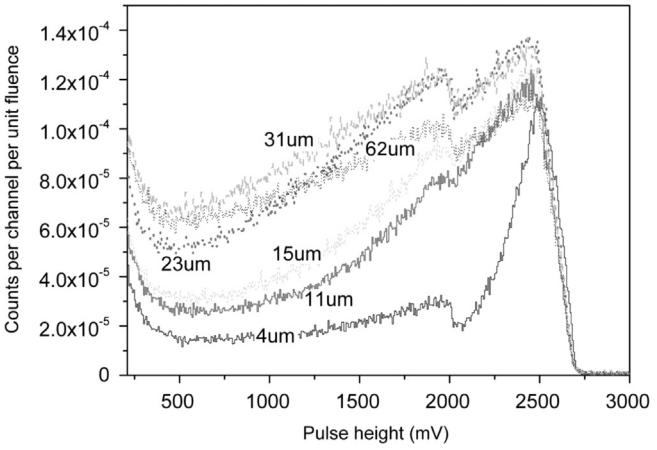

Fig. 2. Pulse height distribution N–N_{Cd} for the TNPD with different thickness exposed to the ex-core thermal field of the TRIGA reactor at power 50 kW. Data are normalized to the unit thermal fluence. Channel width = 3 mV.

plus the following:

$$N_{Cd}(V) = R_{epi}(V) + \gamma(V) + \gamma_{Cd}(V) \quad (2)$$

$$B(V) = S_{th}(V) + \gamma(V) \quad (3)$$

$$B_{Cd}(V) = \gamma(V) + \gamma_{Cd}(V) \quad (4)$$

where $N_{Cd}(V)$, $B(V)$ and $B_{Cd}(V)$ are respectively the PHDs of the TNPD under Cd, of the bare silicon detector, and of the bare silicon detector under Cd.

By combining the equations, the term $R_{th}(V)$ can be obtained by $(N(V)–B(V)–(N_{Cd}(V)–B_{Cd}(V)))$. The four spectra $N(V)$, $N_{Cd}(V)$, $B(V)$ and $B_{Cd}(V)$ are shown in Fig. 1 for the 31 μm detector (highest response) in the TRIGA thermal beam at power 50 kW. Data are normalized to the unit exposure time. The $N(V)$ spectrum shows a double-peaked structure (more evident in Fig. 2), given by the reaction products α and T, having respectively energy 2.05 and 2.73 MeV and range in LiF 6 μm and 30 μm. The conversion coefficient from pulse height to deposited energy is roughly 1 MeV V^{-1}. This was determined by electronic calibration, using a pulse generator, and confirmed by the position of the alpha and triton peaks in the spectrum.

The residual neutron captures in the Cd-covered configuration (N_{Cd}) are due to epithermal neutrons. The same spectrum also shows a photon contribution (region below 500 mV) arising from