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Neutron spectrometer for fast nuclear reactors

M. Osipenko [a], M. Ripani [a], G. Ricco [a], B. Caiffi [b], F. Pompili [c], M. Pillon [c], M. Angelone [c], G. Verona-Rinati [d], R. Cardarelli [e], G. Mila [f], S. Argiro [f]

[a] INFN, sezione di Genova, 16146 Genova, Italy
[b] Dipartimento di Fisica dell'Università di Genova, 16146 Genova, Italy
[c] ENEA, Frascati 00044, Italy
[d] Università di Tor Vergata, Rome 00133, Italy
[e] INFN sezione di Roma II, 00133 Italy
[f] Università di Torino and INFN, Turin 10125, Italy

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ABSTRACT

In this paper we describe the development and first tests of a neutron spectrometer designed for high flux environments, such as the ones found in fast nuclear reactors. The spectrometer is based on the conversion of neutrons impinging on ^{6}Li into α and t whose total energy comprises the initial neutron energy and the reaction Q-value. The ^{6}LiF layer is sandwiched between two CVD diamond detectors, which measure the two reaction products in coincidence. The spectrometer was calibrated at two neutron energies in well known thermal and 3 MeV neutron fluxes. The measured neutron detection efficiency varies from 4.2×10^{-4} to 3.5×10^{-8} for thermal and 3 MeV neutrons, respectively. These values are in agreement with Geant4 simulations and close to simple estimates based on the knowledge of the ^{6}Li(n,α)t cross-section. The energy resolution of the spectrometer was found to be better than 100 keV when using 2.5 or 5 m cables between the detector and the preamplifiers.

1. Introduction

The standard nuclear reactor on-line diagnosis is performed with fission chambers. Solid state detectors have a number of features which distinguish them from gas filled counters. In particular, the much faster carrier drift velocity allows for a rapid charge collection and therefore high counting rate. The high density of the active volume permits spectroscopic measurements with compact detectors which do not alter local conditions. The sensitivity to γs is also lower for solid state detectors because of smaller size and in particular for low-Z detector materials (e.g. for diamond). However, a limitation in the application of solid state detectors to nuclear diagnostics stems from the fact that large non-ionizing energy deposition damages the crystalline structure and alters the properties of the detector. This leads to a reduction of the charge collection efficiency and, in some semiconductors, to an increase of the leakage current. Silicon detectors are strongly affected by this type of damage and cannot be used in high radiation environment. Thanks to the higher displacement energy (43 eV) and the lower Z value, diamond detectors feature up to an order of magnitude larger resistance to non-ionizing doses [1]. Also the diamond shows no leakage current increase after irradiation at room temperature [2]. Therefore, several studies are available in the literature that present their application as diagnostic tools in nuclear facilities.

In addition to radiation hardness, diamond detectors also exhibit a low intrinsic noise at high temperatures thanks to their large bandgap of 5.5 eV. This proposes the diamond detectors for usage in fission reactors where the operating temperature may reach 700° and near fusion plasma chambers, although necessary studies are still on-going. However, the presence of impurities in the diamond crystal creates levels inside the bandgap, thereby increasing the trapping of charge carriers and therefore the charge collection efficiency. High impurity density limited the usage of natural diamonds as radiation detectors. The advent of the Chemical Vapour Deposition (CVD) diamond growing technique enhanced the quality of diamond detectors and allowed practical applications.

Nuclear reactors in which the neutron spectra are dominated by energies well above thermal energies are called fast reactors. These include reactors featuring heavy or low density moderators. A more energetic neutron spectrum allows for a lower production rate of radioactive waste by radiative capture and for the burn-out of a fraction of the long-lived actinides. However, both the reactor dynamics and the burn-out of fuel and actinides depend on the neutron spectrum. Conventionally, the neutron spectrum in a reactor is measured by activation foil analysis. Indeed, the activation of an isotope can be related to the convolution of the neutron flux with the isotope activation cross-section. But this complex, offline, procedure

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introduces large systematic uncertainties. A simple online technique is necessary for characterization of reactor transients. For this purpose we developed a novel neutron spectrometer based on a ^{6}Li converter sandwiched between two CVD diamond detectors. The energy of the incident neutron converts completely into the energy of charged particles through the ^{6}Li(n,α)t reaction. This allows for an event-by-event neutron energy measurement with the advantages of a solid state detector. Moreover, the ^{6}Li(n,α)t reaction is highly exothermic with Q=4.7 MeV, which permits to reduce the background by imposing a high detection threshold. The coincidence between two crystals further suppresses noise and competing reactions.

In this paper we describe the spectrometer assembly and two calibration experiments. The details of detector development are given in Section 2. Measurements of the detector response to thermal neutrons, made at a TRIGA reactor, are discussed in Section 3, while the fast neutron experiment at a DD-fusion source is detailed in Section 4.

2. Detector construction

The sandwich spectrometer prototype was built from two Single-Crystal Diamond detectors (SCD), identified as SCD398 and SCD1517, grown at the laboratories of the University of Rome "Tor Vergata".

Each SCD was grown on a 4 × 4 × 0.4 mm^3 HPHT substrate, and had the same structure, as shown in Fig. 1. These detectors are composed of three main layers: p-type diamond, intrinsic diamond and metal contact. This diode-like structure is described in Refs. [3,4] and allows the readout of signals from the intrinsic diamond layer without removal of the HPHT substrate. The degenerate p-type layer acts as an ohmic contact. Instead, the anode creates a Schottky junction with the underlying intrinsic diamond. In this configuration, the electric current generated by the passage of an ionizing particle in the depletion layer flows across the detector without any barrier. In fact, the Schottky junction at the intrinsic diamond-metal interface accelerates electrons leaving the diamond bulk.

The top contact on the intrinsic diamond side was created by depositing 3 mm × 3 mm × 40 nm Chromium layer, which was also used as a sticking layer for the two narrow (0.4 mm × 3 mm × 80 nm) gold strips shown in Fig. 2. These strips were used to read out the anode signals. On top of the Chromium layer in between the Gold strips a further layer of 3 mm × 2.2 mm × 100 nm of ^{6}LiF was then deposited on the contact. The LiF compound was chosen as a neutron converter because of its chemical neutrality. The selected LiF was enriched with ^{6}Li isotope to 96%. The LiF layer is deposited on the top of the metallic anode in such a way that α and t can easily penetrate into the intrinsic diamond depletion layer with minimal loss of energy. In fact, the assembly leaves only a 50 μm gap to accommodate the central ground microwire.

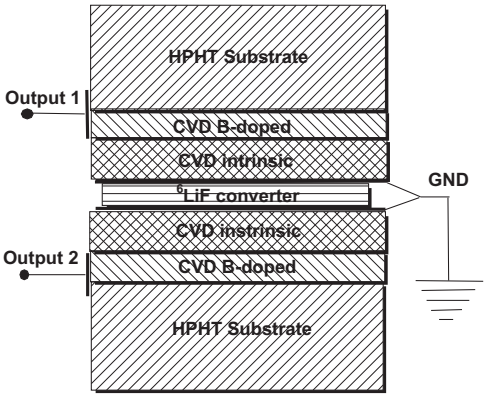

Fig. 1. Design of the sandwich spectrometer with its main components: HPHT diamond substrate, B-doped diamond layer, intrinsic diamond layer, metallic contact and LiF converter.

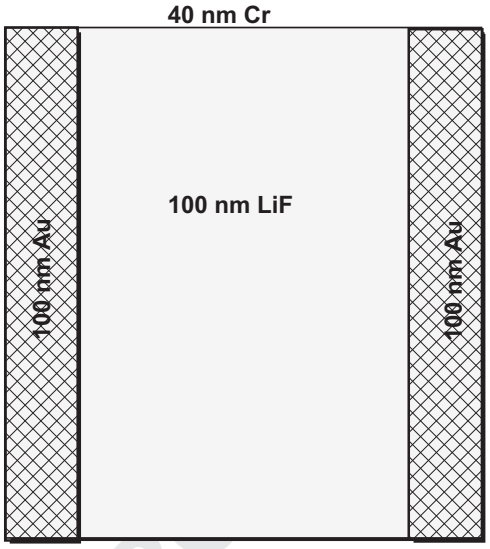

Fig. 2. Gold strips and LiF converter with Chromium contact underneath, deposited on top of the intrinsic CVD diamond crystal.

Table 1
Diamond detector characteristics.

SCD	P-doped layer thick. [μm]	Intrinsic layer thick. [μm]	Cr contact thick. [nm]	LiF layer thick. [nm]
SCD398	23	22	40	100
SCD1517	15	49	40	100

The active volume of each detector consists of its intrinsic diamond layer. The thicknesses of the Boron doped (P-type) and intrinsic diamond layers were different for the two detectors, as shown in Table 1. The thicknesses of the chromium contacts, and of the ^{6}LiF layers, instead, were the same within the uncertainties of the measurement system of the thermal evaporator (Table 2).

The "sandwich" structure is realized by means of two small double-layer Printed Circuit Boards (PCB) (35 μm golden copper on 0.8 mm FR4), to which diamonds are glued. Each PCB has a ground plane on one side and signal traces on the other. The P-type layers are connected to the signal traces with a droplet of conductive glue. The top electrode, which is shared by the two diamonds, is connected by two microwires running along the Gold strips, not covered by LiF, and soldered to the ground plane through four vias. The wires are made of Copper (diameter 50 μm) plated with 2 μm of galvanically deposited gold. Each PCB has four golden-plated connectors which guarantee the integrity of the ground plane and the routing of electrical signals, but also a precise mechanical alignment between the diamonds and the wires when the "sandwich" is closed, i.e. when the two PCBs are joined one to each other. The stability of the electrical contact between the wires and the Gold strips of both diamonds is ensured by a U-shaped spring applies a small force pushing the PCBs one toward the other. The two PCBs have different length, allowing RG62 signal cables to be soldered on dedicated pads on the longer board.

3. Measurement at TRIGA reactor

In order to characterize the detector and to evaluate the absolute amount of ^{6}Li isotope deposited on the sensitive detector area a measurement in a calibrated thermal neutron flux was performed.

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