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Upgrade of the compact neutron spectrometer for high flux environments

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ABSTRACT

In this paper new version of the ^{6}Li-based neutron spectrometer for high flux environments is described. The new spectrometer was built with commercial single crystal Chemical Vapour Deposition diamonds of electronic grade. These crystals feature better charge collection as well as higher radiation hardness. New metal contacts approaching ohmic conditions were deposited on the diamonds suppressing build-up of space charge observed in the previous prototypes. New passive preamplification of the signal at detector side was implemented to improve its resolution. This preamplification is based on the RF transformer not sensitive to high neutron flux. The compact mechanical design allowed to reduce detector size to a tube of 1 cm diameter and 13 cm long. The spectrometer was tested in the thermal column of TRIGA reactor and at the DD neutron generator. The test results indicate an energy resolution of 300 keV (FWHM), reduced to 72 keV (RMS) excluding energy loss, and coincidence timing resolution of 160 ps (FWHM). The measured data are in agreement with Geant4 simulations except for larger energy loss tail presumably related to imperfections of metal contacts and glue expansion.

1. Introduction

Neutron spectroscopy in high flux environments such as fission or fusion reactors is a very challenging task. The standard methods make use of fission chambers or activation foils. However, both of these methods are indirect and they are subject to large systematic uncertainties. They are indirect because observable quantities are related to integrals of neutron spectrum and the unfolding of these integrals gives rise to uncertainties. The spectroscopic application of conventional gas-filled proportional counters with various converters, like ^{3}He, CH_4 and BF_3, is limited to very low neutron energies, where the range of produced charged particles in gas still lies within the detector volume. Scintillators and standard semiconductor based detectors suffer from strong radiation damage. Moreover, scintillators feature strong quenching for low energy ion recoils affecting the energy reconstruction. Diamond is the most radiation hard semiconductor offering a number of beneficial properties [1].

Nowadays diamond detectors are broadly used in the neutron detection in harsh environments [2–8]. However, most of the studies were performed with a single diamond sensor or arrays of independent detectors. A coincidence between two diamond sensors extends capabilities of detector by allowing full energy reconstruction and background reduction.

In Ref. [9] the new neutron spectrometer for such measurements was proposed. It was based on the sandwich of two diamond sensors enclosing ^{6}Li converter. Such device allows to measure neutron energy directly on event-by-event basis applying the energy conservation law. The first prototype of the spectrometer was calibrated in Ref. [9] at two neutron energies and tested in the fast fission reactor in Ref. [10]. These experiments revealed a series of issues leading to degradation of spectrometer performances. In particular, the fast build-up of space charge limited charge collection stability of the spectrometer to relatively low neutron fluences $< 10^{10}$ n/cm^2. Selected diamonds were not very radiation hard [11] and in fact after the experiments, corresponding to accumulated fluence of fast neutrons about 10^{14} n/cm^2, the spectrometer showed an increased instability under the nominal bias voltage. The energy resolution was limited by few meters long cables between the spectrometer and its first amplifier.

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All these issues were dealt with in the work described in this article, resulting in development of the more advanced spectrometer prototype. To suppress space charge build-up new contacts approaching ohmic conditions were deposited. Selection of higher quality diamond crystals also affected charge collection as well as radiation hardness of the spectrometer as explained in Ref. [12]. Implementation of passive amplification scheme near the sensor allowed to improve signal-to-noise ratio and therefore resolution in spite of long cables and fast electronics used. Furthermore, resolution on the coincidence time between two diamond sensors was improved by more than one order of magnitude. In the following sections the new spectrometer is described in details along with new characterization measurements performed at the TRIGA reactor with thermal neutrons and at the Frascati Neutron Generator (FNG) neutron source with 2.5 MeV neutrons.

2. Detector upgrade

In the new prototype of the sandwich spectrometer, commercial, electronic grade single crystal CVD diamonds from E6 [13] were used. The diamonds were 300 μm thick and had surface area of 3×3 mm^2. Almost the entire top and bottom surfaces were covered with thin metal contacts. All the samples were cleaned in a strongly oxidizing solution (H_2SO_4 : $HClO_4$: HNO_3 in the 1:1:1 ratio, 15 min at boiling point), followed by rinsing in aqua regia (HCl : HNO_3 in the 3:1 ratio, 5 min at boiling point) and ultrasound sonication, in order to remove organic and metallic impurities, possible non-diamond contents, and residual debris. Metallization procedure on top and bottom surfaces of diamond samples consisted of the formation of a <3 nm-thick Diamond-Like Carbon (DLC) layer by energetic (700 eV) Ar+ ion bombardment, able to induce amorphization of the diamond surface. Resistivity of the layer was estimated by 2-point measurements to be around 10^8 Ωcm. DLC ultra-thin layers at diamond–metal interface were indeed demonstrated to improve contact ohmicity and stability under high-flux irradiation [14]. Subsequently, a 100 nm-thick Au layer was grown in situ by RF magnetron sputtering (RF power 200 W, base pressure 10^{-6} mbar, Ar^+ pressure 2.3×10^{-2} mbar). Lateral dimensions of the contacts (2.8 x 2.8 mm^2) were defined by stainless steel shadow masks positioned on the diamond surface during both the DLC layer formation and Au layer deposition processes. The improved ohmicity of the electric contacts, mostly induced by the quality of the DLC layer produced on the diamond surface, allowed for the fabrication of ionizing radiation detectors [15–17] with reduced build-up of space charge under the device electrodes. At the borders of contact area two 200 μm wide and 150 nm thick strips were added, similar to those in Ref. [9].

On one diamond 100 nm thick LiF film enriched with ^{6}Li to 96% was thermally evaporated on the metal contact. The evaporation was performed inside an evaporation chamber evacuated down to the pressure of 10^{-6} mbar. The LiF powder was poured inside a tungsten crucible, electrically connected to its power supply. The samples were mounted on a sample holder located over the crucible with a quartz microbalance being placed on the same plane. Margins of diamond surface were covered with the same stainless steel mask used for metal contact deposition. The thickness was controlled during deposition by the microbalance. The expected ratio of the subtended solid angles from the sample holder and the microbalance was estimated to be about 0.4. After the deposition the effective thickness of deposited film was measured to be 100 nm using an interferometer microscope.

The diamond sensors were glued with conductive glue E-solder 3025 [18] at opposite sides of a 250 μm thick double-face PCB, above a square through-hole of size slightly smaller than the diamond dimension, as shown in Fig. 1. This procedure requested development of a special tool for holding the diamonds at their expected positions above the hole during curing time. This way most of diamond inner (w.r.t. PCB inserted in the middle) surfaces were not obscured by PCB and charged particles could travel from one diamond to the other, losing energy only in about 300 μm of air. On the PCB circuit the inner diamond

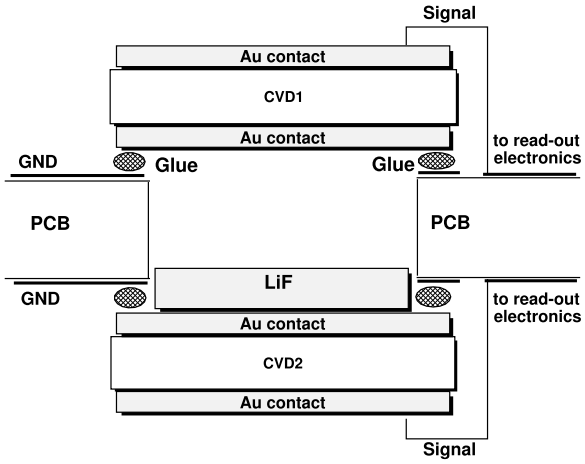

Fig. 1. Vertical projection of the spectrometer drawing (not in scale) around its sensitive part. CVD1 and CVD2 indicate two diamond crystals, each of them have metal contacts on its top and bottom surfaces. Diamonds are glued to PCB at the edges of square hole leaving large fraction of detector area open.

contacts were set to ground by conductive glue, while the outer contacts were connected to high voltage bias and signal readout vias by wedge bonding.

Electronic grade single crystal CVD diamond features a very large effective resistance, in 1 V/μm electric field it reaches $10^{14} \div 10^{15}$ Ω. Thus it can be approximated as an ideal current source with infinite intrinsic impedance. In the present application the Si-based amplifier cannot be installed near to the detector due to large flux of fast neutrons. These neutrons would damage Si-based electronics much faster than the diamond sensor. Few meter long coaxial cables must therefore be used to carry detector signals outside of high radiation region. Given the typical impedance of coaxial cable (50 Ω for RG174) it is recommendable to transform the signal maximizing its voltage amplitude before entering into the cable. This was accomplished by means of a fast RF transformer as shown in Fig. 2. For this purpose we selected Mini-Circuits T14-1-KK81 RF transformer [19], which features relatively high impedance ratio of 14 and wide bandwidth of 150 MHz. The diamond detector signal, which extends to higher frequencies, is integrated and shaped by the transformer enhancing considerably its decay time. This allowed to amplify voltage amplitude of the signal by a factor 3 shifting its main frequency into the range less affected by cable attenuation. In fact the transformation renders the output signal very similar to Si detector response, recovering the difference in the number of eh-pairs produced per unit energy and increasing rise-time and fall time. The comparison of the diamond detector response to 5 MeV α-particle with the signal amplified by the RF transformer is shown in Fig. 3. The amplified signal is much larger, but has a longer decay time.

PCB had dimensions of 8.5×80 mm^2 and it was inserted into aluminum tube with external diameter of 10 mm, which provided the shielding against EMI. The dimension of the tube was chosen for compatibility with small channels in fast reactors like Venus-F [20].

The output signals from the PCB were connected via 3.5 m RG174 cables to Wantcom WBA0010-45A [21] amplifiers. These amplifiers have bandwidth of 1 GHz and they provide gain of 45 dB introducing minimal amount of noise. Also the lower edge of accepted frequency band of 10 MHz allowed to suppress environmental noise. The signals were amplified further by a Phillips Scientific 771 amplifier. The final signals were acquired by SIS3305 digitizer at sampling rate of 5 Gs/s. The custom Data AcQuisition (DAQ) system was running on Concurrent Tech. VX813-09x single board computer saving data to a fast SATA SSD. More details on DAQ may be found in Refs. [9,12].