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N3G project: front-end electronics and mechanical advances

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Abstract: The higher counting-rate and radiation hardness required by modern gamma spectroscopy experiments highlight the need for a new generation of High-Purity Germanium detectors based on electrons-collecting electrodes. To achieve this goal, new doping technologies are required. The one studied by the N3G (Next Generation Germanium Gamma detectors) project is the Pulsed Laser Melting. Besides the development of innovative segmented High-Purity Germanium crystals, the project is also aimed at developing a detector case complete of contact structures and front-end electronics. A specific integrated circuit pre-amplifier is being designed: a first version was tested at room temperature, using a pulser as pre-amplifier input. A resolution of 1.08 keV with 15 pF input capacitance, reproducing the one of a detector single segment, was obtained with 6 µs shaping time.

Keywords: Analogue electronic circuits; Detector design and construction technologies and materials; Front-end electronics for detector readout; Gamma detectors (scintillators, CZT, HPGe, HgI etc)

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Contents

1 Introduction

Segmented High-Purity Germanium (HPGe) detectors are widely used in modern gamma-spectroscopy experiments because of their excellent energy resolution and unprecedented positional resolution when used with tracking technique, as demonstrated by the experimental campaigns with the arrays AGATA [1] and GRETINA [2]. The energy resolution is given by the physical properties of High-Purity Germanium, while the positional resolution is obtained by segmenting the external electrode of the detector and by applying tracking algorithms. The induced charge on neighboring segments gives information on the points where the gamma-ray released part of its energy. Comparing this information with the ones stored in a database, the Pulse-Shape-Analysis (PSA) algorithms allow to reconstruct the positions of the gamma-ray interactions with an accuracy of 5 mm FWHM [3, 4].

The state-of-the-art electrodes are realized by ion implantation of boron for the p^+ contact, the one collecting holes, and diffusion of lithium for the n^+ contact, the one collecting electrons. Because of the high diffusivity of lithium in germanium, the n^+ contact can be 0.5 mm–1 mm thick, being a dead layer where no charge collection occurs and preventing any segmentation procedure [5]. As a consequence the segmented electrode is the p^+ one, and the tracking analysis is performed on holes-signals. Since holes are much more subjected to trapping induced by neutron damage, the effect of this technological limitation is a resolution worsening [6]. Since higher event rate and more severe radiation environments are expected in the next few years experiments, the neutron damage may increase, as a result of 10^9–10^{10} neutrons/cm^2 fluence. This is the reason why detector technology improvements are mandatory. Specifically, the development of innovative doping techniques to realize external electrons-collecting electrodes is essential. As a matter of fact, electrons are less likely to interact with the neutron-induced traps. In this framework the N3G project was born.

N3G is a four-years project funded by the Italian National Institute for Nuclear Physics (INFN). The main goal consists of the implementation, management and maintenance of complex coaxial segmented HPGe detectors with n^+-doped external electrode, realized by applying the innovative Pulsed Laser Melting (PLM) technique [7, 8]. Together with the aspects strictly concerning the

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detector crystals, this project includes the development of cryogenic containment and contact systems. The use of state-of-the-art discrete pre-amplifiers is foreseen, together with the development of dedicated, innovative, integrated Charge-Sensitive Pre-amplifiers (CSP). In this work the general project strategies are presented, together with the preliminary results obtained with the room-temperature characterization of the first ASIC (Application Specific Integrated Circuit) CSP prototype.

2 Mechanical developments

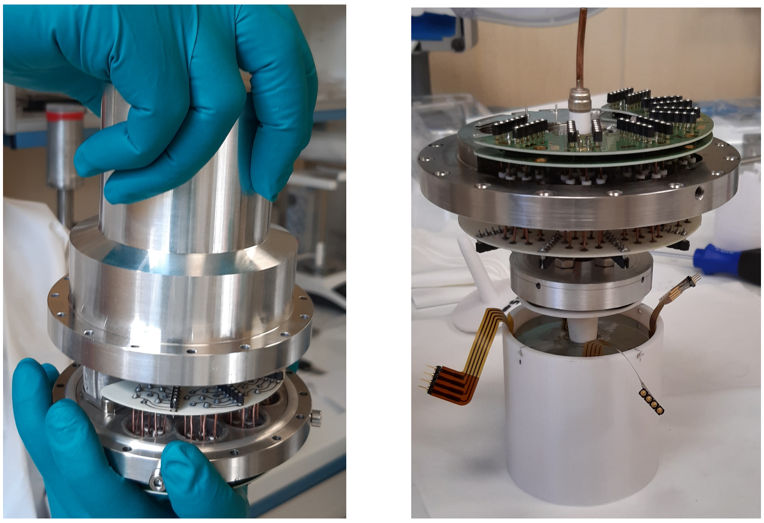

Figure 1. Vacuum-tight canister (left). Detector assembled on the designed mechanical system (right).

The first coaxial segmented detector produced for the N3G project has a cylindrical profile: it is 50 mm high and its diameter is 50 mm wide. The external n$^+$-doped surface is divided in 12 lateral segments and 4 frontal segments, while the bottom surface is passivized and must not be touched by mechanical or electrical elements. HPGe detectors must be housed in vacuum-tight canisters. In such a way the detector can be preserved from contaminants that may induce surface leakage currents. To achieve this goal an aluminum cylindrical case was designed (figure 1-left). It also works as an IR (Infra-Red) shield and it is closed by a stainless steel flange housing both the electrical feed-through connectors and a vacuum inlet. Moreover, a porous getter can be included to improve the vacuum quality when activated. Although the flange material is not transparent to γ radiation, it can be used to realize this component since it is placed on the opposite side with respect to the radiation entrance window.

The HPGe crystal is supported by a hollow conical body made of alumina. It fits together the inner electrode by means of a protective indium layer, introduced to avoid any mechanical friction with the electrode itself. Inside the cone an electric rod is placed. It is used to apply the high-negative voltage (3 kV–5 kV) needed for the detector polarization. The base of the cone is located on a stainless steel single-wave annular spring, placed inside an aluminum spring-holder, directly screwed to the flange. The systems made by detector, cone, spring and spring-holder is closed by a PEEK (PoliEther-Ether-Ketone) cylindrical case to firmly keep the crystal in position independently from the container absolute orientation (figure 1-right).

Because of the small band-gap of 0.7 eV, germanium detectors must work at cryogenic temperature. As a matter of fact, room-temperature operations are not possible, because of the extremely large thermally-induced leakage current that would result. As a consequence, the canister containing and protecting the detector must be placed inside a cryostat [9]. To meet this need and to simplify the test operations, the flange was design to be completely compatible with the cryostats available at LNL (Legnaro National Laboratories).

3 Connection system

Figure 2. Flexible PCB wrapped around the detector.

The connections of the electrodes of the detector must guarantee a good electrical contact, even at cryogenic temperatures, without scratching their brittle surface. A flower-shaped flexible PCB (Printed Circuit Board) was realized for this purpose. It is made on a 36 µm thick Kapton (polyimide) substrate and it is designed to be wrapped around the detector, as shown in figure 2. The copper contacts of the flexible PCB are flashed with gold and lean against the external electrode segments. The flexible PCB is then connected with pin strips to a rigid one, which is shaped according to the constraints set by the geometry of the feed-through connectors. Through these components, signals are sent outside the canister to the PCB housing the input transistors of the CSPs (Charge Sensitive Pre-amplifiers), kept at cryogenic temperature by the cold finger in order to minimize the electronic noise. The high voltage rod has a dedicated feed-through that reaches the inner contact of the detector and ensures electrical connection with a small, spring-loaded clip.

4 Electronic developments

The N3G front-end electronics is based on an ASIC pre-amplifier realized in AMS C35B4C3 (350 nm) technology. Two different versions of the charge-sensitive pre-amplifier are being designed. The first one is integrated [10] and developed to be placed inside the cryostat. It makes use of a p-MOS input transistor. The second one, instead, requires an external JFET input transistor. Thanks to the latter configuration it is possible to divide the front-end electronics, placing the input transistor inside the cryostat at cryogenic temperature and the CSP outside it at room temperature [11]. The design of a cryogenic CSP is particularly challenging, since no transistor models are available for such a low temperature. For this reason, we want to characterize various test structures at Liquid Nitrogen (LN) temperatures and create custom models to perform simulations.

The first prototype of fully-integrated CSP was tested at room temperature on a dedicated test bench using a pulser. A 15 pF capacitor was used to reproduce the single segment capacitance. The pre-amplifier is equipped with a feedback path consisting of an external 1 GΩ resistor in parallel with an integrated 0.2 pF feedback capacitor. The choice of a discrete resistor is determined by the necessity to minimize the parallel noise contribution [12–14]. The CSP is characterized by a 8 MeV dynamic range which can be extended up to 40 MeV, thanks to an innovative fast-reset circuit [15]. The extension of the conventional dynamic range of the pre-amplifier above the saturation threshold allows also the reconstruction of the energy deposited by any heavy ion impinging on the detector and the reduction of the dead time when the saturation occurs.

Table 1. ENC and energy resolution for 1 MeV interactions.

τ [µs]	ENC [e_{rms}]	FWHM [keV]
0.5	244	1.71
1	204	1.42
2	173	1.21
3	163	1.14
6	155	1.08
10	154	1.08

For energies below the saturation threshold, the pre-amplifier works in a conventional way. It produces exponential-type signals with leading-edge fall-time of the order of 20 ns and a time constant of 200 µs. The circuit Equivalent Noise Charge (ENC) was measured feeding the CSP output to a commercial Quasi-Gaussian shaping amplifier. The results obtained for different shaping times τ are reported in table 1. With the optimum shaping times of 6 µs and 10 µs, the best energy resolution of 1.08 keV FWHM was obtained. Although the state-of-the-art discrete-components CSPs can have slightly better resolution, their large power consumption must be taken into account. For instance, the pre-amplifier developed in the framework of the PANDORA experiment achieves an energy resolution of 0.8 keV FWHM with a power consumption of 200 mW. This is much greater than the 10 mW power consumption of the integrated CSP designed for the N3G project [16].

The innovative fast reset circuit equipping the CSP allows to retrieve the energy information on the interactions that saturate the pre-amplifier. By means of a constant current generator the charge deposited on the input node of the CSP is collected. The time required for the complete charge collection is proportional to the charge released during the saturation interaction plus the residual charge due to the pre-event baseline level [17, 18]. Other solutions have been developed to remove the contribution from the baseline itself [19]. The CSP behavior during the reset phase is pictured in figure 3. When the output signal crosses a predefined threshold ("start-of-reset threshold"), the reset phase is activated. The pre-amplifier remains in saturation until enough charge is removed from its input. Recovering from saturation, the CSP output voltage comes back to its quiescent voltage level with a constant slope naturally determined by the value of the feedback capacitor and the reset current.

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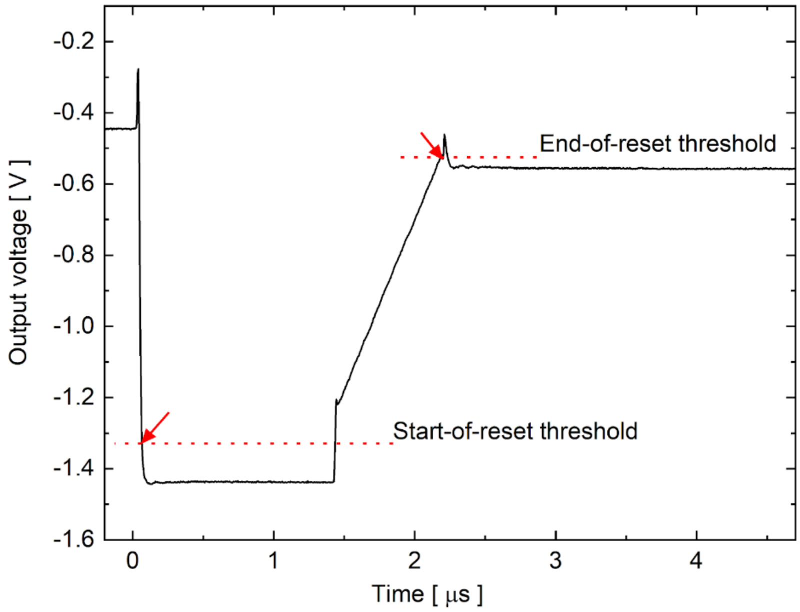

Figure 3. Fast-reset signal for a high energy event that brings the CSP into saturation. The time duration of the signal is proportional to its energy.

When the signal crosses a second predefined threshold ("end-of-reset threshold") the reset ends and the CSP is ready to work again in the conventional mode. While the reset is active the CSP outputs an auxiliary rectangular waveform that can be profitably used to measure the duration of the procedure.

Table 2. Linearity (columns 1 and 2) and energy resolution (columns 3 and 4) of the fast-reset circuit. In the last column the FWHM is reported in terms of percentage of the measurement.

Time [ns]	Energy [MeV]	FWHM$_{res}$ [keV]	FWHM_res [%]
822.5	8.15	15	0.18
1266.0	12.22	15	0.13
1707.6	16.30	18	0.11
2152.2	20.37	17	0.08
2599.0	24.44	18	0.07
3046.0	28.52	18	0.06
3492.5	32.59	19	0.06
3940.8	36.67	19	0.05
4387.3	40.74	19	0.05

The linearity and resolution measurements for this operational configuration were performed with a 2-GS/s oscilloscope and are reported in table 2. Considering the simulation of events impinging on the detector with energy greater than 15 MeV, the relative resolution obtained is better than 0.11 % FWHM. The relative resolution at 8 MeV in reset mode, below the 0.2 %, is probably the best result obtained so far with such technique.

5 Conclusions

The developments of the N3G project are still ongoing. The first results obtained with the integrated electronics look very promising and pave the way for future developments and tests, especially at cryogenic temperatures. Great effort is being spent on guaranteeing the mechanical/electrical compatibility of this system with the cryogenic setups available among the collaboration, including the mechanical support of the cryostats cold fingers and the external electrical connections.

Acknowledgments

This work is submitted on behalf of the N3G collaboration.

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