Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A prototype High Purity Germanium detector for high resolution gamma-ray spectroscopy at high count rates

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ARTICLE INFO

Article history:
Received 23 January 2015
Received in revised form
22 April 2015
Accepted 24 May 2015

Keywords:
Gamma-ray detectors
High-Purity Germanium
Amorphous semiconductors
High count rate

ABSTRACT

Where energy resolution is paramount, High Purity Germanium (HPGe) detectors continue to provide the optimum solution for gamma-ray detection and spectroscopy. Conventional large-volume HPGe detectors are typically limited to count rates on the order of ten thousand counts per second, however, limiting their effectiveness for high count rate applications. To address this limitation, we have developed a novel prototype HPGe detector designed to be capable of achieving fine energy resolution and high event throughput at count rates in excess of one million counts per second. We report here on the concept, design, and initial performance of the first prototype device.

1. Introduction

High Purity Germanium (HPGe) detectors remain the recognized gold standard for high-resolution gamma-ray spectroscopy [1,2]. The excellent energy resolution that HPGe detectors afford often makes them the detector of choice for applications as diverse as nuclear physics research, medical imaging, homeland security, and environmental monitoring [2]. Where isotope identification and quantification are required, the fine energy resolution of HPGe detectors minimizes the systematic uncertainties associated with the analysis of photopeaks in the presence of background continua. This is particularly important in cases where complex gamma-ray spectra are likely to be encountered.

Historically, the use of HPGe detectors has been limited to applications where the count rate is reasonably low. Conventional large volume HPGe detectors are typically limited to operating at count rates of less than a few tens of kcps due to the combination of relatively long charge collection times and significant signal rise-time variations that characterize such devices, as well as the need to employ relatively long pulse shaping times in order to minimize the effects of electronic noise. Various approaches to the high rate operation of HPGe spectrometers have been proposed and typically focus on the use of very small detectors, novel electronics and data acquisition systems, or algorithmic solutions [3–6]. Typically, energy resolution, detection efficiency, or event throughput (i.e. the fraction of absorbed events for which an energy may be measured) must be sacrificed in order to achieve increased count rate.

There are several nuclear safeguards applications that require high-resolution gamma-ray spectroscopy to be performed at very high count rates. Prime examples are the assay of spent nuclear fuel pins and assemblies for the verification of burn-up in the presence of intense backgrounds from ^{137}Cs and other fission products, and non-destructive assay for quantification of U and Pu isotopes in samples of various types [7]. In both of these applications, the challenge is to maintain spectroscopic performance, efficiency, and high event throughput at input count rates on the order of one million counts per second. Energy resolution is required for quantitative isotopic analysis while high throughput and good efficiency are required in order to minimize the measurement time.

When considering the tradeoff between energy resolution and event throughput at very high count rates, one is typically forced to decide which of the two competing performance criteria is most important for the given application. Performance gains in one area are therefore achieved at the cost of losses in the other. However, this trade off is typically not a forgiving one and conventional HPGe spectroscopy systems that offer high resolution and high throughput at low count rates quickly transition into a regime characterized by both low throughput and poor energy resolution as the incident rate becomes large. Often, the trade off is complicated further by the relationship between detection efficiency, detector volume, and charge collection time. In many applications, such as those in nuclear structure physics, for example, the desire to maintain detection efficiency at high gamma-ray energies makes the use of large-volume detectors

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http://dx.doi.org/10.1016/j.nima.2015.05.053
0168-9002/© 2015 Published by Elsevier B.V.

appealing. The inherently long charge collection times associated with these detectors then limits the count rate performance that may be realized given the length of the pulse shaping times required to achieve fine energy resolution.

For applications such as the non-destructive assay of spent nuclear fuel, the high statistics nature of the measurement scenario, as well as the ability to employ a multi-detector arrangement to increase the total detection efficiency at high energy, results in the prioritization of throughput and energy resolution over the need to achieve high detection efficiency with a single detector. In order to maximize the fraction of incident events that may be processed, pulse pile up must be reduced through the use of short shaping times. However, when these shaping times become sub-optimal for a given system, the energy resolution is degraded [8]. In the case of conventional digital trapezoidal shaping [9], two major components typically contribute to this degradation: ballistic deficit resulting from the selection of a gap time (i.e. flat top time) that is too short given the rise time of the signals from the detector, and insufficient filtering of the electronic noise due to the selection of a sub-optimal value of peaking time.

The current implementation of the Ultra High Rate Ge (UHRGe) system, developed at Pacific Northwest National Laboratory, comprises a standard closed-end coaxial HPGe detector read out through a wide dynamic range charge sensitive preamplifier. The data acquisition system employs standard digital electronics and custom pulse processing algorithms designed for high rate spectroscopy. The best performance achieved with this system to date is ~8 keV FWHM at 662 keV with 39% throughput at an input count rate of 1 Mcps. This is compared to around 2.0 keV FWHM at 662 keV and a throughput of close to 100% at rates on the order of 1 kcps. A detailed discussion of this system and its performance can be found in Ref. [10].

In this work we present details of a novel prototype HPGe detector developed for the second generation UHRGe system. This device is based on a planar geometry and employs a modified single-sided strip electrode configuration. The device was designed to provide high performance while also offering a relatively low channel count over a large surface area, as well as a straightforward readout scheme. The electrode configuration features one-dimensional electrical segmentation of the front face of the detector and a continuous (i.e. full area) contact on the back. Electrical segmentation of HPGe detector contacts is increasingly common in state of the art device gamma ray tracking arrays as well as devices for gamma ray imaging. Large gamma ray tracking arrays such as AGATA and GRETINA [1,2] employ radial, longitudinal, and azimuthal segmentation to the implanted outer contact of coaxial HPGe detectors in order to achieve improved position sensitivity. Each individual segment is typically several cubic cm in volume with each segment representing a reasonably large surface area. In a strip electrode configuration, the electrode on each face of a planar crystal may be individually segmented in one dimension, with segmentation occurring orthogonal to the axis in which charge is collected.

In designing a device capable of achieving improved resolution and throughput at Mcps rates, we have focused on a detector geometry that offers fast charge collection and short signal rise times, and a segmented electrode scheme that allows the incident rate to be distributed over multiple channels. At the short shaping times required for this application, the contribution from capacitance-driven series noise dominates the electronic noise induced peak broadening [11]. Because of this, our prototype device features a segmentation scheme designed to offer only a modest capacitive load to the input of the preamplifiers. Our design philosophy is grounded in providing flexibility in the tradeoff between throughput and energy resolution, providing excellent energy resolution and high throughput at count rates on the order of 1 Mcps, while also allowing users to incur relatively small losses in energy resolution for significant increases in throughput and/or rate capability.

In this paper, we describe the design of the detector and present calculated predictions of its performance. We then summarize the measured performance of the prototype device and consider the future development of this technology.

2. Theoretical methods

Prior to fabrication of the prototype detector, and in establishing the design, a combination of analytic and numerical calculations was used to estimate the theoretical performance of the device. In Ref. [12], idealized analytic expressions for the parallel, series, and 1/f contributions to the total electronic noise as a function of shaping time are presented. A framework for modeling the performance of a given detector design based upon these expressions, as well as analytic solutions to the device capacitance, was established. This framework was used to assess the impact of various electrode designs on electronic noise and energy resolution.

For our design studies, we assumed a 15 mm thick planar HPGe detector with an active area of 80 mm × 80 mm. A single sided strip electrode configuration comprising ten strips was chosen in order to adhere to the constraints of large area, relatively low channel count, and straightforward readout scheme. We therefore assumed an electrode geometry with a strip pitch (P, defined as the center-to-center strip spacing) of 8 mm and strip length of 80 mm. Fig. 1 shows a schematic representation of the basic geometry employed in the design studies. For all calculations the detector was assumed to be fully depleted and with a leakage current of 20 pA per strip. This estimate is a conservative one in comparison with typical measured values of 10 pA per strip. Finally, we defined some additional properties related to an assumed preamplifier configuration operated with a warm front end, operating at 300 K. We assumed a Field Effect Transistor (FET) with a leakage current of 1 nA, a capacitance of 1 pF, and a transconductance of 5 mA/V and a feedback circuit comprising a 1 pF capacitor and 100 MΩ resistor. Our assumptions for the FET were based on typical values associated with a JFET while those of

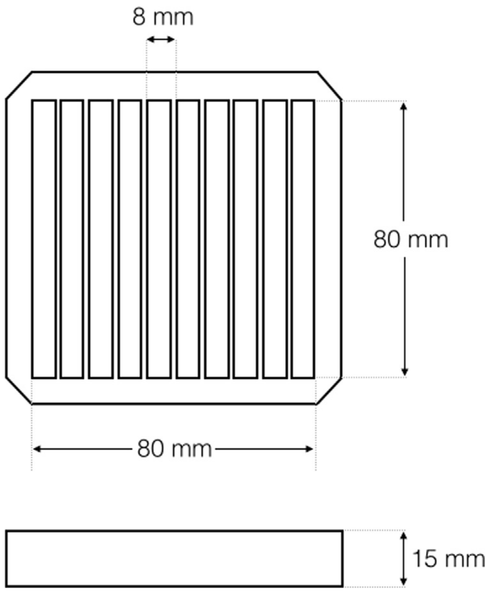

Fig. 1. Schematic representation of the basic geometry employed in the design study. The electrically segmented front face of the detector is shown.

Please cite this article as: R.J. Cooper, et al., Nuclear Instruments & Methods in Physics Research A (2015), http://dx.doi.org/10.1016/j.nima.2015.05.053