An Integrated Low-Noise Charge-Sensitive Preamplifier with Virtually Unlimited Spectroscopic Dynamic Range*

*Patent Pending

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***Abstract*–A low-noise ASIC preamplifier for semiconductor detectors has been built and characterized, which is able to provide a linear spectroscopic measurement of the detector charge signals even when its output voltage is saturated. The preamplifier works in a conventional mode, i.e. as an active current integrator, when the output signal is below a preset threshold. If the signal is larger the preamplifier operates in a non-standard controlled fast-reset mode, which is effective in providing a linear measurement of the detector signal charge even when the preamplifier works close to or in saturation. The experimental relation between the measurement and the input charge keeps perfectly linear irrespective of the non-linearity of the preamplifier working regime, which yields a dynamic-range boost of more than one order of magnitude.**

I. INTRODUCTION

NEXT generation nuclear-physics experiments to be executed in international dedicated facilities, like GSI, LNL, and GANIL in Europe, will employ highly-segmented HPGe (High Purity Germanium) detectors for gamma-ray measurement and tracking [1]-[5], and will make use of radioactive ion beams to investigate the nuclear structure under very extreme condition of stability. Both the detectors and the front-end electronics will have to work in new and hostile conditions that could substantially spoil their spectroscopic performance. One of the most critical issues is related to the foreseen background of charged particles, like pions or kaons with energies up to 100 MeV or more. When an energetic charged particle hits a detector crystal it gets fully absorbed and generates a huge charge signal that can easily put the front-end electronics in a prolonged saturation state, paralyzing the system and compromising its functionalities. So, it is of paramount importance that the front-end is capable to properly manage such large charge signals. The simplest way to address this issue is the use of discrete-component preamplifiers working on very high power supplies of ±12V or ±24V [6]-[14]. These preamplifiers can reach a huge energy range of ~150MeV while keeping the typical noise performance required for gamma-ray spectroscopy. But discrete-component circuits are very bulky and consume some hundreds milliwatt per channel when using such large power supplies. For next-generation highly-segmented detectors the use of ASIC preamplifiers is going to become mandatory, because the channel density and the power budget requirements are getting incompatible with discrete-component solutions. So the question is: how to treat extra large charge signals with an integrated preamplifier?

The use of high power supplies is not viable with integrated circuits owing to the "scaling down" process, which yields a lower and lower breakdown voltage for the individual devices. As an example the maximum rating for power supplies is ±2.5V in a 0.35 μm CMOS technologies widely used for low-noise analogue designs. Using so low power supplies the output voltage swing of an integrated charge-sensitive preamplifier for semiconductor detectors is typically about ±1.5V This translates into an energy range of 10 MeV when using the typical sensitivity of 150 mV/MeV as needed to achieve energy resolutions of 0.1-0.2% @ 1-2MeV with a noise floor < 1keV fwhm. So there is no way to impede that an ASIC preamplifier enters a saturation state when the aforementioned energetic charged particles hit the detector, and the discussion should be mostly focused on how to usefully treat a saturated preamplifier. In this paper we discuss this carefully and introduce an innovative circuit technology for ASIC charge preamplifiers that yields

(i) a short recovery time from overloads caused by large signals. As an example a 100 MeV signal is fully reset in 10μs
(ii) the ability to perform a precise and linear measurement of the amplitude of the detector signals that cause preamplifier saturation

Using the proposed technology the measurement dynamic range of a single ASIC preamplifier may easily reach the unprecedented figure of 10^5.

II. TECHNIQUE

In this Section we briefly describe the technique used in the integrated Charge-Sensitive Preamplifier (CSP) we have designed, realized and test bench characterized. It embodies a patented cutting-edge circuit technology [15] that makes high-resolution amplitude measurements possible also in the case of detector signals so large to cause a soft or deep saturation of

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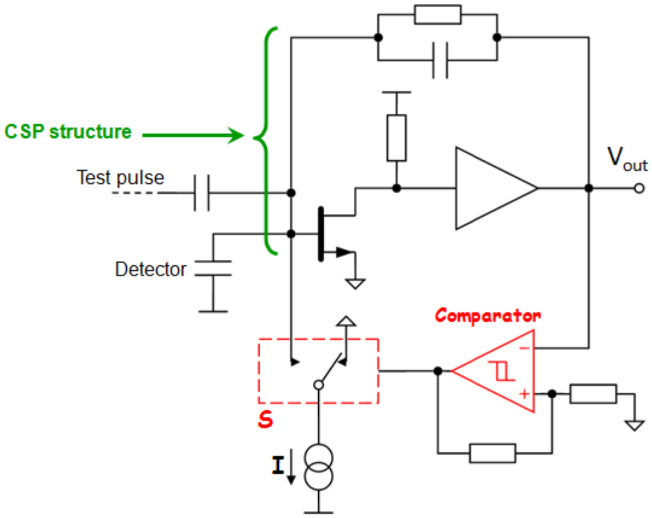

Fig.1. Simplified schematic diagram of the realized preamplifier. The controlled fast-reset feature is implemented through a Schmitt-trigger camparator, a constant current sink “I”, and a double-throw CMOS switch “S”.

the charge preamplifier. A simplified schematic diagram of the circuit is shown in Fig. 1.

The upper part of the circuit is a negative-feedback JFET-CMOS CSP with continuous-time resistive reset [16]-[19], or, in other words, a low-noise active current integrator. The innovation consists of the three more devices shown in the lower part of the circuit: a Schmitt-trigger comparator, a precise constant current sink “I” and a double-throw CMOS switch “S” connected to the input node of the circuit. When the events are gamma rays of typical amplitude, i.e. a few MeV or a few hundreds millivolt as translated in terms of output voltage, the comparator stays in its low state, which keeps the switch in the right position. At this time current “I” is flown to ground and does not interfere with the CSP action of the circuit. But when a signal overcomes a preset threshold the comparator commutates to its high state, which drives the switch to the left position. At this time current “I” is forced to flow through the input node of the preamplifier, which begins a process of controlled removal of the physical charge provided by the detector. The process is controlled because driven by a precisely constant current “I”. The larger is “I” the faster is the charge removal process. When the output voltage gets back to the zero volt baseline the comparator back commutates to its low state and the charge removal process terminates, which closes the controlled fast-reset phase. We set “I” in such a way that the reset time is ~10μs for a 100MeV energy release into the germanium detector. Notice that the larger is the signal charge delivered by the detector, the longer is the time required to fully remove it at a given removal rate. The key point is that reset time is strictly proportional to the charge by the very definition of electrical current. Current in fact is charge over time, and a constant current removes a precise amount charge per unit time. There is no way out of this and the linearity property is going to hold irrespective of the working regime of the preamplifier, even if it is highly non-linear over most part of the reset process.

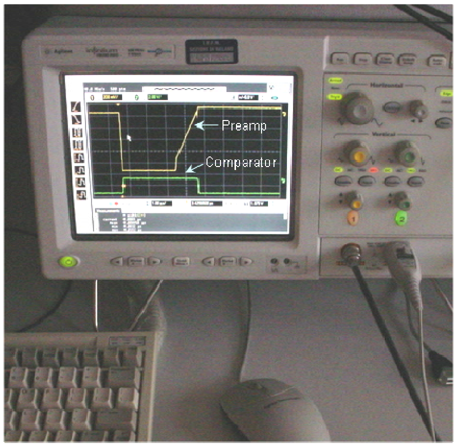

Fig. 2. Signals seen on the oscilloscope. The upper track is the preamplifier output signal in response to a large over-threshold test signal. The lower track is the corresponding comparator signal.

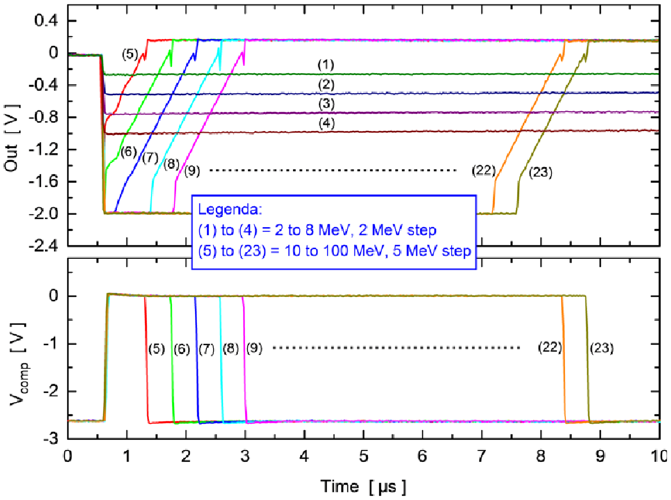

Fig. 3. Experimental response of the circuit to test pulses equivalent to events of 2 to 100MeV in germanium. On top and bottom the signals seen at the preamplifier and the comparator outputs are shown.

III. CIRCUIT REALIZATION AND FIRST CHARACTERIZATION

The circuit has been realized as a prototype in a low-noise 5V 0.35μm CMOS technology, and characterized in the lab. The first signals which prove the functionality of the fast reset feature are shown in Fig. 2 as seen on the scope.

In Fig. 3 a set of such signals is shown for input signals of increasing amplitude. In the upper part of the figure the preamplifier output signals are shown. Signals from (1) to (4), or from 2 to 8 MeV, are under the comparator threshold and hence the circuit behaves like a conventional CSP providing step signals with a slow exponential decay in the ms time scale. Signals from (5) to (23), or from 10 to 100 MeV, are over threshold and hence the circuit executes a controlled fast reset of the signal charge. For these cases the relevant signals

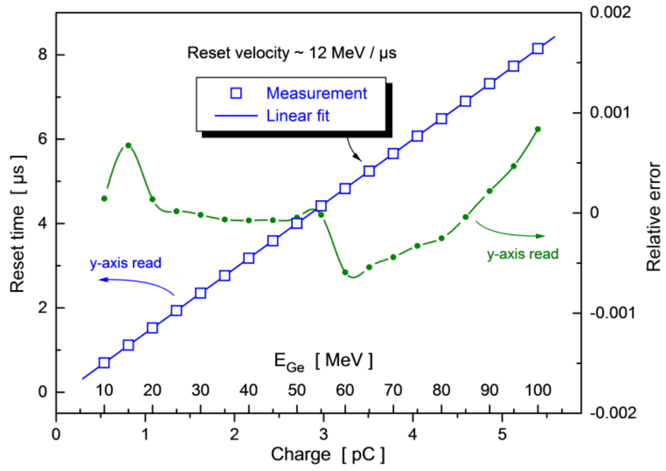

Fig. 4. Plot of the widths of the comparator signals, i.e. the reset times, as a function of the test pulse amplitudes in terms of injected charge or equivalent energy in germanium.

are those seen at the comparator output, shown in lower Fig. 3. As said the width of these signals, or the reset times, is expected to be strictly proportional to the signal charge itself. In Fig. 4 this property is shown where the experimental reset time is plot vs. the signal charge generated by the events. The x-axis shows also the equivalent event energy considering the energy-to-charge conversion factor of germanium of 2.92eV/pair. The relation is indeed linear in the full range of available experimental data. Evaluating the deviation of the experimental data from the linear fitting a non linearity error is obtained below ±0.1% over the full range. We have observed that the irregular behavior of the error at 15 and 55 MeV is more related to the instrumentation used for the measurement than to the circuit itself. This proves experimentally the concept of controlled fast reset.

In Fig. 5 the response of the circuit is shown to a sequence of an extra large event of 40 MeV and a much smaller event of 1 to 9 MeV occurring only 4 µs after. Typically the second event could not be observed ought to a prolonged saturation of the preamplifier lasting 1ms or more. But thanks to the controlled fast-reset feature the large signal pulse lasts 3 µs only and the second event is cleanly revealed. This feature would be very useful in decay spectroscopy applications.

In Fig. 6 the room temperature Equivalent Noise Charge of the circuit is shown as a function of the shaping time for detector capacitances of 0 and 15 pF (lower and upper curve). The fitting to the experimental data and the three disentangled typical noise components are also shown. [20]. The noise is ~160 r.m.s. electrons with a detector capacitance of 15pF at a shaping time of 6µs, which is fully adequate for gamma spectroscopy. The noise is expected to diminish further when installing preamplifier in the detector cryostat and cooling it at cryogenic temperature. Another way to improve the noise would be use of a higher quality laminate for the PCB where the input transistor is mounted. In fact as shown in Fig. 6 the dominant noise contribution comes from the flat component (blue dashed line), related partly to the 1/f noise of the input transistor but mostly to the dielectric noise of the insulators surrounding the input node of the preamplifier [21].

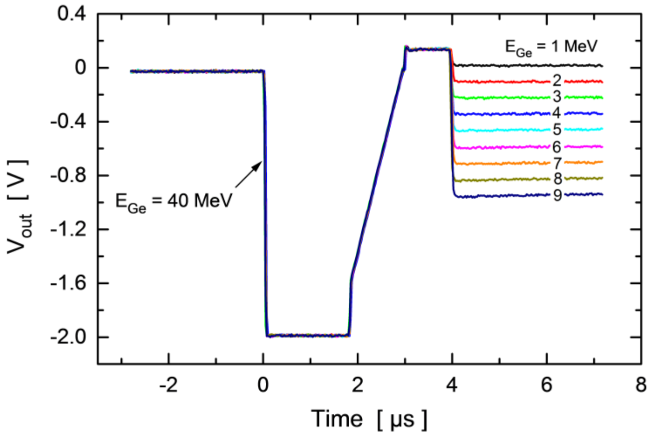

Fig. 5. Response of the preamplifier to a sequence of an extra large (40 MeV) and a smaller signal (in the 1 to 9 MeV range). The smaller signals.occur only 4 µs after the large one but are cleanly resolved.

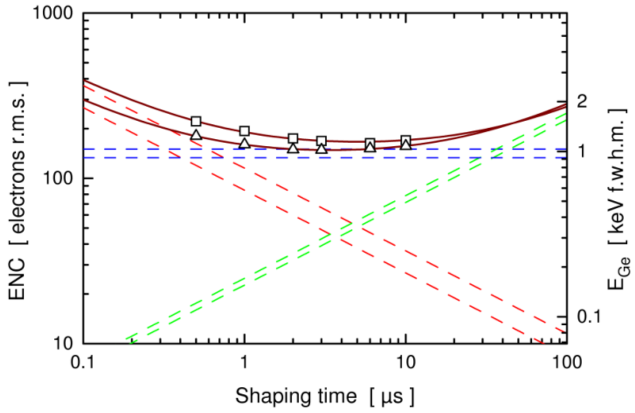

Fig. 6. Equivalent Noise Charge of the preamplifier vs. shaping time as taken at room temperature. The lower and upper curves are for detector capacitances of 0 and 15pF. The fitting to the noise data and the three typical disentangled noise contributions are also shown.

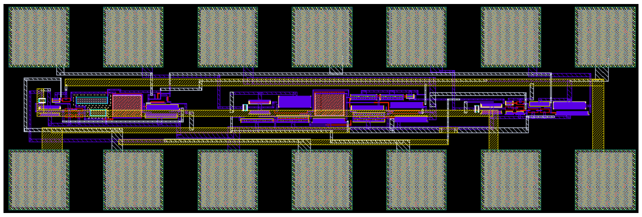

Fig. 7. Layout of the realized chip. The area occupancy is 700 × 100 µm^2 excluding the bonding pads. The size of each bonding pad is 90 × 90 µm^2

The layout of the tested circuit is shown in Fig. 7. The area occupancy is 700 × 100 µm^2 excluding the bonding pads, and the power consumption is ~30mW.

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