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Sub-nanosecond time-of-flight for segmented silicon detectors

R.T. deSouza [a,]*, A. Alexander [b], K. Brown [a], B. Floyd [a], Z.Q. Gosser [a], S. Hudan [a], J. Poehlman [b], M.J. Rudolph [a]

[a] Department of Chemistry and Center for the Exploration of Energy and Matter, Indiana University, Bloomington, IN 47405, USA
[b] Department of Chemistry, Indiana University Bloomington, IN 47405, USA

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ABSTRACT

Development of a multichannel time-of-flight system for readout of a segmented, ion-passivated, ion-implanted silicon detector is described. This system provides sub-nanosecond resolution ($\delta t \approx 370$ ps) even for low energy α particles which deposit $E \leq 7.687$ MeV in the detector.

1. Introduction

Low-energy beams of radioactive ions present unique opportunities in the field of nuclear science and nuclear astrophysics. The availability of neutron-rich beams of oxygen, for example, allows one to address whether the probability for near-barrier fusion is enhanced due to the neutron-richness of the colliding system. Whether an enhancement exists is an important open question in understanding the properties of neutron star crusts and fusion dynamics [1]. However, the low energy radioactive beams necessary for such astrophysical studies also present some specific challenges. Foremost among these challenges is the identification of low-energy ions on an event-by-event basis. While digital pulse shape digitalization techniques show significant promise for A and Z identification of incident ions, at present this approach is limited by its significant identification threshold [2]. A well-established low threshold technique for the detection and identification of low-energy ions is by measuring their time-of-flight and energy [3]. Using this technique, in experiments aimed at measuring the fusion excitation function, one could distinguish fusion residues from elastically scattered beam or other reaction products. Silicon detectors which can handle rates up to a few kHz without a degraded response are ideally suited to radioactive beam experiments which operate at extreme values of N/Z and consequently are low intensity beams or low intensity stable beam experiments.

For the past 30 years time-of-flight measurements utilizing surface barrier detectors have been able to achieve time resolutions, δt, of ≈ 100 ps with resolutions of < 300 ps routinely reported in the literature [4,5]. However, such detectors are typically relatively small, < 400 mm^2 in area. Over the past couple of decades, silicon detectors have been developed that utilize ion-implantation and passivation techniques, Si(IP) [6]. Advances in silicon wafer processing with these techniques now make it possible to fabricate detectors utilizing 6 in. and even 8 in. wafer technology. Moreover, while their large area makes feasible tiling a large area with silicon with high geometric efficiency, these detectors are usually highly segmented which maintains a low detector capacitance. While uniform neutron transmutation doped silicon with digital sampling techniques have been shown to provide time resolution of ≈ 100 ps [7], application of this approach to highly segmented detectors would require high quality analog signal multiplexing or a large number of digitizers. We have therefore decided to investigate the time-of-flight capabilities of highly segmented Si(IP) detectors with discrete electronics. In this article we report on the development and implementation of a multichannel system using discrete electronics capable of sub-nanosecond time resolution.

2. General description

Depicted in Fig. 1 is a block diagram illustrating the approach used. Signals from one segment of a silicon detector are split by a passive frequency dependent splitter. The splitter divides the signal between the fast amplifier and the charge sensitive amplifier. The transition frequency is 7.5 MHz with the rising edge sent through a LC high pass filter to the fast amplifier. The input impedance of the splitter is chosen to be 50 Ω to match the coaxial cables from the detector. The signal to the charge sensitive amplifier is delayed by a low pass LC filter, but all of the charge is transferred in ≈ 300 ns.

* Corresponding author. Tel.: +1 812 855 5815; fax: +1 812 855 6645.
E-mail address: desouza@indiana.edu (R.T. deSouza).

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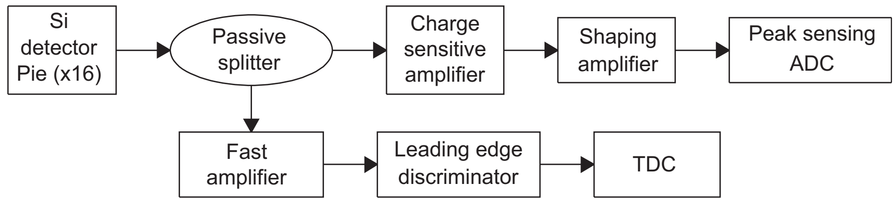

Fig. 1. Block diagram of the electronics for processing the signals from the ohmic side of a segmented Si(IP) detector.

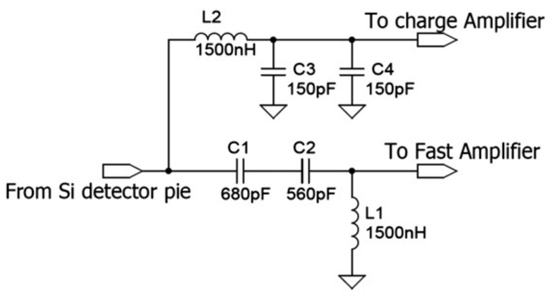

Fig. 2. Circuit diagram of the splitter circuit.

Following the charge sensitive amplifier, the slow signals are processed by a shaping amplifier and a peak-sensing analog-to-digital converter (ADC). The output of the fast timing amplifier acts to edge-trigger a leading edge discriminator and the resulting logical signal is used to provide a stop signal for a time-to-digital converter (TDC). This relatively standard approach with discrete electronics has been successfully implemented with surface barrier detectors in 1970s [8]. In the present work we explore how well this approach works with a large area segmented Si(IP) detector.

3. Description of the electronic design

The schematic of the passive splitter and the fast timing amplifier developed are shown in Figs. 2 and 3. Components were chosen so as to provide high quality signal processing at a modest component cost of $\approx$\$25 per channel.

In the fast amplifier circuit, amplification is provided in two stages by two monolithic amplifiers, MAR-8ASM+ and GALI-74+ from Mini-Circuits [9]. Cascaded, these amplifiers provide a gain factor of ≈ 450 for the input signal. The single channel amplifier circuit shown is realized in a two-layer printed circuit board measuring 1.5 in. $\times$ 4.8 in. As evident in Fig. 4, the layout used is quite spacious as for the intended application space was not a design constraint. We conservatively estimate that due to the highly linear layout of each channel and separation of each channel on its own board, the total size of the layout could be reduced by a factor of three without compromising the performance of the circuit. In order to process multiple signals from a segmented detector, multiple channel boards can be configured into a multi-channel system. Governed by the segmentation of the silicon detector used we have developed a multichannel system consisting of 16 independent channels. It is important to note that in order to prevent cross-talk of adjacent channel boards it was necessary to provide grounded copper shields that eliminate cross-talk between the second stage of the amplifier and its neighboring channel.

4. Performance of the system

The response of the fast timing amplifier to real signals was investigated by coupling the electronics to a ion-implanted passivated silicon strip detector from Micron Semiconductor [6]. This annular detector, Design S2, consists of 16 pie shaped sectors on the ohmic side and 48 annular rings on the junction side. Signals from each pie shaped sector were processed by the electronic chain depicted in Fig. 1. In contrast, signals from each ring were processed by conventional charge-integrating, peak-sensing electronics thus providing redundant energy information. The detector used had a nominal thickness of 290 μm and a nominal depletion voltage from the manufacturer of 50 V. The capacitance of a single pie shaped sector is approximately 70 pF.

In a vacuum chamber the detector, overbiased to a voltage of -150 V, was illuminated by a ^{226}Ra source with the particles entering the pie side of the detector. The emitted α particles with energies ranging from 4.601 to 7.687 MeV typically penetrate a depth of 22–47 μm. Signals from the detector propagated through coaxial 50 Ω cable (RG-316) $\approx$ 35 cm long prior to reaching the passive filter. To reduce fast pickup on these cables, they were housed in a metal conduit effectively acting as double shielded cable. A typical fast signal from the fast timing amplifier is displayed in Fig. 5. The fast signals exhibit a typical risetime of 5–6 ns. The overshoot of the signal acts to limit the maximum rate at which this electronics can be utilized. However, as this electronics is principally being developed for relatively low rate experiments with radioactive beams ($I < 1 \times 10^6$ particles/s), this rate limitation does not present a limitation of any significance.

In order to evaluate the time resolution of the electronics developed, we inserted a time zero detector (TZD) in the path of the α particles and measured their time-of-flight together with their energy. This time zero detector consisted of a 20 μg/cm^2 carbon foil from which electrons ejected by the passage of an α particle were accelerated and reflected from wire grids before being amplified by a microchannel plate assembly. This time zero detector has a well-established conventional design [10]. Prior to this work we measured the time resolution of the time zero detector to be 210 ps by measuring the time-of-flight of a mono-energetic α source between two identical time zero detectors. Signals from the time zero detector were discriminated by a constant fraction discriminator (Tennelec 455) and provided the start signal for a Caen V1290 TDC [11].

The stop signals for the TDC were taken from the pie signals of the silicon detector following the fast timing amplifier and discrimination by a Caen V895 leading edge discriminator as previously described. The TDC, as well as an ADC for energy information, were read out by a PC/VME based multiparameter data acquisition system [12].

Depicted in Fig. 6 is the two-dimensional spectrum of energy vs. time-of-flight for α particles emitted from the ^{226}Ra source. The spectrum shown consists of superimposing the data from all pie shaped sectors on the detector by utilizing a linear calibration. The prominent feature of the spectrum is five distinct peaks corresponding to the well-known α energies of the source at 4.784, 5.489, 6.002, and 7.687 MeV. The sixth peak at 4.601 MeV, though visible when one projects on the energy axis, is not clearly visible in the two-dimensional plot due to its low intensity. Also evident is a locus of points between the α peaks and extending to lower energies. Points along this locus correspond to α particles degraded in energy by the carbon foil and wires planes of the TZD. By selecting the high energy α peak we examined the time resolution for a fixed energy. The time