Detection of pulsed neutrons with solid-state electronics

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Measurements of the spatial and time-resolved characteristics of pulsed neutron sources require large area detection materials and fast circuitry that can process the electronic pulses readout from the active region of the detector. In this paper, we present a solid-state detector based on the nuclear activation of materials by neutrons, and the detection of the secondary particle emission of the generated radionuclides' decay. The detector utilizes a microcontroller that communicates using a modified SPI protocol. A solid-state, pulse shaping filter follows a charge amplifier, and it is designed as an inexpensive, low-noise solution for measuring pulses measured by a digital counter. An imaging detector can also be made by using an array of these detectors. The system can communicate with an interface unit and pass an image to a personal computer.

Keywords: Fast neutron detection; Solid-state electronics.

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1. Introduction

Pulsed neutron sources can emit a high yield of fast neutrons and therefore require high performance neutron detectors to resolve the energy spectrum and to evaluate the total yield.¹ The detection of pulsed neutron sources has to be synchronized to the repetition rate of the source, and the detection system must integrate the signal over several emission pulses for an acceptable signal-to-noise ratio when the yield per shot is low.² For many applications, neutron detectors must have a fast response, be portable and inexpensive, and should be deployed with a large detection area. Solid-state detectors can fulfill these requirements. The most common method for neutron detection is through the use of scintillators that convert the absorbed neutron energy into light, which can be detected using photodiodes, photomultipliers or CCDs (Charge Coupled Devices). Scintillators are sensitive to many kinds of ionizing radiations including gamma rays,

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their efficiency is relatively low, and they are only viable with a high gain light detector.³ For low yield neutron sources, the nuclear activation technique can offer better discrimination from other ionizing radiations when compared to scintillation detection techniques. The nuclear decay of activated materials occurs on the order of the half-life of the material, and the decay can release secondary radiations such as beta particles in the region of one per square centimeter for an incident fluence of 400 neutrons per square centimeter.⁴ Wide active area silicon detectors can be used, for example a p-i-n diode or avalanche photodiode, to detect the beta emission. The charge produced as the secondary particle passes through the diode can be measured using a charge amplifier. Wide active area avalanche diodes have a prohibitive cost, especially when developing a detector that will require many diodes to provide spatial resolution. Low cost p-i-n diodes have a high capacitance that increases the system noise and therefore reduces the overall sensitivity of the detector. In recent years, the development of low-noise electronic devices has made possible the implementation of inexpensive, low-noise charge amplifiers capable of operating at room temperature. In our application, the electrical pulse produced from the energy deposition in the diode of the secondary particle is measured with a charge amplifier. The output from the charge amplifier is fed to a pulse shaper that limits the bandwidth and so reduces the noise. An inexpensive, solid-state detector, based on the neutron activation of beryllium and the detection of the secondary particle emission of the activated product's decay, is presented in this paper. The detector utilizes a microcontroller capable of communicating using a modified SPI protocol. A wide area image sensor can be made by using an array of these detectors.

2. Principles of the Detector Operation

Naturally occurring beryllium is composed predominantly of ^9Be . When a fast neutron is incident onto the beryllium, a (n,α) reaction occurs that produces ^6He and a prompt α -particle. The helium-6 subsequently decays with a half-life of 800 ms into a dominant beta channel (99.99%). The beta has an endpoint energy of 3.5 MeV. The detection of this beta in a solid-state device is the basis for detecting the neutrons. The beryllium is coupled to an array of diodes so that spatial information about the distribution of the neutrons can be discerned, and the detector can be used as a fast readout neutron camera for radiography applications.

3. Design Considerations

In order to design a charge amplifier for a wide area p-i-n photodiode, the most significant factor is the input voltage noise level.⁴ Such a charge amplifier commonly uses a Junction Field Effect Transistor (JFET) as an input element. A very low input noise can be achieved by using them in parallel.⁵ A good estimate of the input voltage noise is given by $e_n = \sqrt{8KT/3g_m}$, where K is the Boltzmann constant, T is the absolute temperature and g_m is the JFET parallel combination transconductance. BF862 JFETs are inexpensive low-noise, low gate leakage devices commonly used in charge amplifiers. Although these devices are very popular in the input stage of charge

amplifiers, they have the disadvantage of having wide range of values for I_{DSS} (saturation drain current) and $V_{GS(off)}$ (cut-off voltage), which affects the system input noise. Alternatively, the 2SK932 from “ON Semiconductor” can be used to give better results at the charge amplifier input stage.⁶ The 2SK932 is classified by I_{DSS} in three different ranks with a minimum 7.3 mA to a maximum 24 mA. This limits the I_{DSS} variation of the 2SK932 to a ratio of 1.7 against the 2.5 of the BF862. Same type of JFETs that operate at a predefined quiescent current provide the maximum transconductance if they have I_{DSS} equal to the quiescent current. If one has a higher I_{DSS} , then it will provide lower transconductance in the predefined current. In a charge amplifier, the quiescent current at the JFET input stage is the product of the minimum I_{DSS} multiplied by the number of the parallel JFETs. Under these conditions, a large I_{DSS} JFET will provide lower transconductance and consequently higher input voltage noise. To have low noise, it is better to use two parallel JFETs with low I_{DSS} than one JFET of the same type with the double I_{DSS} . The limit for using JFETs in parallel depends upon the charge amplifier input capacitance, which becomes equal to the detector capacitance, resulting in an inconvenient maximum number of input components for high capacitance detectors. Two 2SK932-22 type JFETs are used at the input stage of the charge amplifier. According to the additional data provided by ON Semiconductor, we expect about 35 mS forward transfer admittance for each JFET for the proposed circuit that is shown in Fig. 1.

Fig. 1. The proposed charge amplifier circuit.

To operate the p-i-n photodiodes with a relatively high bias voltage, the photodiode is connected in such a way that its bias voltage is blocked from the circuit input. In this way the input capacitor (C1) of the charge amplifier does not have to be charged to the bias voltage, and the circuit has a faster start up. According to the BF862 datasheet,⁷ the JFET gate current can be affected by the JFET drain voltage. For this reason, the drain voltage of the parallel connected JFETs is kept low ($\sim 1.7V$). However, this may affect the operation of the folded cascode PNP Bipolar Junction Transistor (BJT). Therefore, the feedback RC (R_F, C_F) network is connected directly to the amplification node to ensure the PNP BJT (Q3) operates with enough V_{CE} to function correctly. At this node, the voltage goes negative due to charge collection by the feedback capacitor (C_F).

The three NPN transistors that follow the charge amplifier form a high input impedance, low-noise and low power consumption inverting preamplifier. This circuit has an input impedance of about $1\text{ M}\Omega$, and the amplification is kept low to nearly 20. This allows for the provision of a significantly lower-cost operational amplifier for the pulse shaping filter. R12 and C6 form a high pass filter with a much lower cut-off frequency compared to the pulse shaping frequency. This filter reduces the low frequency noise and interference to prevent saturating of the amplifier. Figure 2 shows the circuit of the pulse shaping filter. The pre-amplified signal feeds the MC33078 dual operational amplifier as an inexpensive and low-noise solution. The MC33078 circuitry forms a second order band-pass filter with center frequency about 15 kHz . The filter is also used for the signal final amplification. The total amplification can be adjusted relative to the p-i-n photodiode output signal (different type or bias condition) from the voltage divider that is formed from the resistors $R \times 1 = 3.9\text{ k}\Omega$ and $R \times 2 = 510\text{ }\Omega$.

Fig. 2. The pulse shaping filter circuit.

The circuit described above is the analog part of a pixel of the image sensor and drives the pulses to an analog comparator. The image sensor consists of an array of 64 photodiodes connected to 32 units. Each unit has two photodiodes with two charge amplifier circuits, filters, analog voltage comparators, and a single low-cost ultra-low power microcontroller (Texas Instruments MSP430F2132) as shown in Fig. 3. The

microcontroller counts the pulses from the comparators outputs. Also, this microcontroller can set the threshold voltage of the voltage comparators using the integrated Pulse Width Modulation (PWM) peripheral circuit.

Fig. 3. a) Block diagram of a two pixel unit and b) image of the device.

The 32 units form a simple network with a master microcontroller using a high speed modified bidirectional SPI Bus (Fig. 4). The master microcontroller communicates with a PC through a serial port. The modified SPI communication bus has three signals: CLK (synchronization signal), MOSI (master output slave input) and MISO (master input slave output). The CLK and MOSI signals are the outputs from a master and the input signals to all slaves. Similarly, the MISO is an input signal from a master but a tri-state for all slaves. This MISO signal switches to the output state only when it needs to send data to the master. In addition, two more signals are used, the RST in order to reset the slave microcontrollers, and the trigger pulse to initialize the dual selector. When the slave receives the trigger pulse, it connects the photodiodes to integrators through the selector, which connects the photodiodes to the charge amplifiers in order to start the counting.

Fig. 4. Communications block diagram of the image sensor.

A protocol has been implemented for the communication between the master and the slave microcontrollers. All data transfers can be started only from a master. Each slave microcontroller has its own address. The master microcontroller communicates with each slave periodically with a frame of 8-bit words:

Slave Address	Command	Payload	Data 1	Data 2	...	Data n	CRC
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The first byte is the address of a slave to which a request is made. Zero value of this field indicates command to all slaves. The second byte is the command. The available commands are shown in Table 1.

Table 1. Master controller commands.

Command Value	Slave Action
00	Reset Counters
01	Start Counting
02	Stop Counting
03	Set Comparator 1 threshold voltage
04	Set Comparator 2 voltage
10	Read Counters

The payload field contains the number of bytes to be transferred, and thereafter, n bytes of data are transferred. The final field is a CRC value in order to detect errors in communication.

The procedure to get the measurements of one shot is:

- The trigger signal initializes the slave and master microcontrollers. The slave resets the counters and places the selector to integrators position in order to produce the appropriate threshold voltage for voltage comparators. The master initializes memory to obtain data from slaves.
- After a few microseconds, the integrators complete the current integration from photodiodes and the slave places the selector to charge amplifier position. This immediately starts the counting of comparator output pulses.
- After few seconds, the master sends the stop counting command to all slaves and starts the readout of the results.

The final step is the graphical representation of 64 photodiodes data on the PC. The master microcontroller sends the data from 64 counters to a PC through the serial port.

4. Experimental Results

The initial experimental results were obtained by using betas from the neutron activation of beryllium (Be) and by using a ^{90}Sr source that emits a beta with sufficient energy to propagate into the active layer of a diode. Several configurations of p-i-n photodiodes were successfully tested under different reverse bias conditions. In Fig. 5, the output signal from a PS100-7 p-i-n photodiode is shown when irradiated with betas from the ^{90}Sr source. With only 5 V reversed bias, a depletion region of less than 100 μm and a capacitance higher than 100 pF are expected.

Fig. 5. Shaped pulse from a PS100-7 diode biased with 5V (500 mV/div and 100 $\mu\text{sec/div}$).

From the initial result, it is apparent that the analog part of the pixel circuit has enough signal-to-noise ratio (SNR) to detect the particles, even with very low reverse bias to the p-i-n photodiode. Higher reverse bias will increase the active layer of the

photodiode and will also decrease the capacitance. Both are beneficial to improve the signal-to-noise ratio.

5. Conclusion

A solid-state detector based on nuclear activation caused by neutrons and detection of the secondary particle emission of their decay is presented. The detector utilizes a microcontroller capable of communicating using the modified SPI protocol. An image sensor can be made by using an array of these detectors. The system can communicate with an interface unit and pass an image to a personal computer. A charge amplifier and pulse processing circuitry coupled to large area p-i-n diodes as particles detectors is designed and optimized.

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