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A hand-held neutron detection sensor systems

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Abstract

In this paper, a hand-held neutron radiation sensor application is described. The sensor system utilizes a new class of boron-carbide diode that interacts with incoming neutrons. To interface with the boron-carbide diode an integrated front-end is designed in a 1.5/spl mu/m standard CMOS technology. With the diode and front-end microchip, a hand-held neutron detection system was realized with an embedded microcontroller for realtime processing. The hand-held detector operation was then tested with a plutonium-beryllium neutron source. Testing results confirm the validity of the approach and the functionality of the design.

A Hand-Held Neutron Detection Sensor System

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***Abstract*— In this paper, a hand-held neutron radiation sensor application is described. The sensor system utilizes a new class of boron-carbide diode that interacts with incoming neutrons. To interface with the boron-carbide diode an integrated front-end is designed in a 1.5μm standard CMOS technology. With the diode and front-end microchip, a hand-held neutron detection system was realized with an embedded microcontroller for real-time processing. The hand-held detector operation was then tested with a plutonium-beryllium neutron source. Testing results confirm the validity of the approach and the functionality of the design.**

I. INTRODUCTION

A compact, reliable, and accurate neutron detection system can have many different application possibilities. Systems no larger than a cigarette pack could be used to screen shipping containers entering a country for hazardous or illegal radioactive materials. Baggage could quickly be screened at airports around the world. The monitoring nuclear weapons, reactors, and stored materials in remote locations could also greatly benefit from such a system. The larger and less reliable gas and liquid neutron detectors currently available are not practical for such applications.

Existing and proposed solid-state neutron detectors also suffer from very low efficiencies, and are not suitable for harsh environments [1]. However, recent work has created a new and unique class of solid state boron-carbide semiconductors, which possesses potentially excellent neutron detection properties [2]-[4]. These boron-carbide (B-C) diodes have been observed to accurately detect single neutrons, giving very high efficiencies. Boron-carbide also has excellent mechanical properties, making it resistant to harsh environments.

The goal of this work is to realize a hand-held neutron detecting sensor system utilizing this new class of diode. First, the properties and operation of B-C diodes are briefly described. The following section presents an integrated charge amplifier circuit and other components as a sensor front-end. Next, the design and architecture of a hand-held neutron detector is presented. Finally, test results of both the integrated circuit and hand-held detector are presented.

II. BORON CARBIDE NEUTRON DETECTOR

Boron is a very useful element for the application of neutron detection, and is unique in the fact that it is able to form boron-carbide. Moreover, boron-carbide is a ceramic that can resist high temperatures and extreme environments. The basis of detecting neutrons with boron is well-known, and is based on $^{10}\mathrm{B}_{(\mathrm{n},\alpha)}{}^{7}\mathrm{Li}$ capture giving

$$\begin{aligned} {}^{10}B + n &\rightarrow {}^{7}Li(0.84MeV) + {}^{4}He(1.47MeV) \\ &\qquad + \gamma(0.48MeV) \\ &\text{or} \\ {}^{10}B + n &\rightarrow {}^{7}Li(1.02MeV) + {}^{4}He(1.78MeV) \end{aligned} \quad (1)$$

with 94% and 6% probabilities, respectively. Thus, an incoming thermal neutron strikes a ^{10}B atom producing ^{7}Li and ^{4}He. These capture products travel through the semiconductor with initial kinetic energies given in (1), and a substantial number of electron-hole pairs are generated as they lose kinetic energy.

Recently, more newer, efficient all boron-carbide devices (”heteroisomeric diodes”) have been created which use different polytypes of the plasma-deposited films to give both the n-type and p-type layers to construct the diodes [4]. These B-C diodes have then been used to create the first real-time, solid-state neutron detectors. Experiments have shown a minimum generation of 10^5 electron-hole pairs generated per neutron, creating current pulses in the range of hundreds of nanoamps for 10μs to 40μs durations. With very high collection rates of the electron-hole pairs, and operation from at least 20°C to 350°C, these detectors are more efficient and reliable than any other neutron detecting semiconductor reported to date.

III. SENSOR SYSTEM DESIGN

A. Front-End Microchip Design

The ability of the charge amplifier to convert small charge signal inputs to a voltage signal make it particularly useful as a particle detector interface [5], [6]. The low-noise charge amplifier used here as the neutron detector front-end was first presented in [7], [8]. The topology of the amplifier is shown in Fig. 1, and was designed in a 5V 1.5μm n-well CMOS process.

The core of the charge amplifier consists of the folded-cascode pair M1 and M3, and active load M4. The cascode structure provides the charge amplifier with a high open-loop gain and large frequency bandwidth. The output of the folded-cascode pair is then buffered with a source follower created by transistors M5 and M6. The source follower then biases the input through feedback transistor MF.

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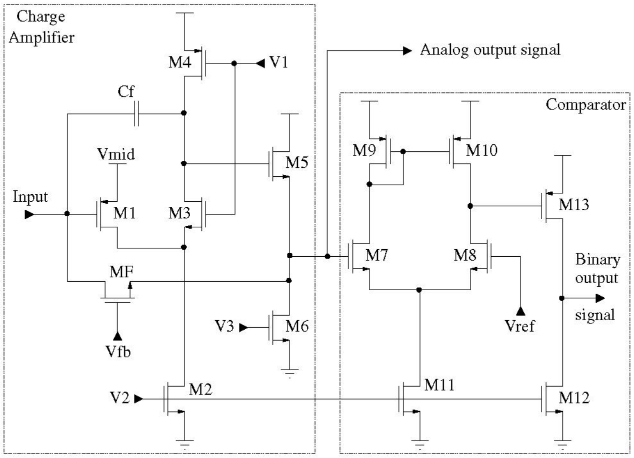

Fig. 1. Circuit schematic of the charge amplifier and comparator used in the integrated sensor front-end for interfacing with the boron-carbide diode.

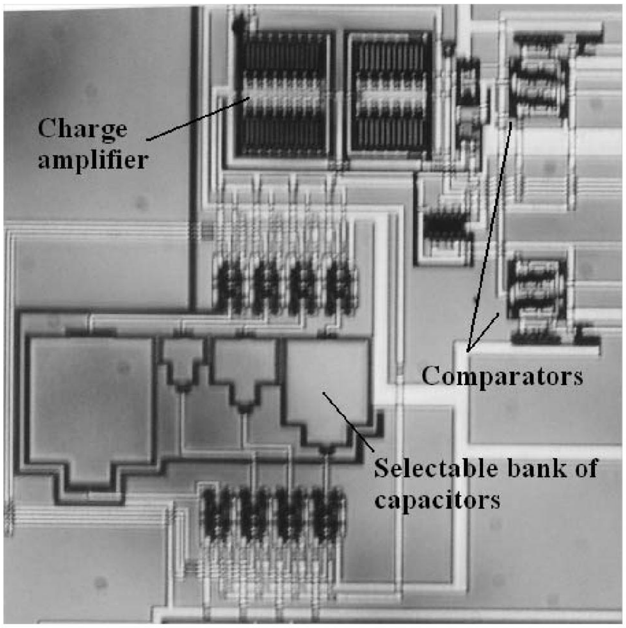

Fig. 2. Die photo of the integrated front-end showing the charge amplifier, comparators, and configurable bank of capacitors.

Without the feedback transistor and capacitor, the open-loop gain A_0 is given by

$$A_0 \approx -g_{m1}\left((r_{ds1}g_{m3}r_{ds3})\,||r_{ds4}\right) \tag{2}$$

which is dominated by the drain to source resistance r_{ds4}. The source follower pair M5 and M6 is approximated as unity gain in (2). With feedback capacitor C_f the ideal closed-loop form of the charge-to-voltage conversion gain A is given by

$$A \approx \frac{1}{C_f}. \tag{3}$$

The B-C diodes are placed under reverse-bias during detection and capacitively coupled to the charge sensitive amplifier. Current pulses resulting from neutron capture events flow from the input to ground, causing the stored charge in C_f to change, varying the voltage at the input node. That small voltage change is then amplified at the output as a positive-going voltage peak. A controllable feedback then causes the output voltage to decay to a steady-state DC value, and will prevent the amplifier from saturating due to close arriving charge transfers.

To create a digital pulse signal from the charge amplifier and provide a degree of noise rejection, a simple comparator is implemented. The comparator circuity is also show in Fig. 1, and consists of a n-type differential pair amplifier coupled with a p-type common-source amplifier. An n-type differential pair is used so that the DC output level of the charge amplifier can properly bias input transistor M7. The addition of the common-source amplifier provides a near rail-to-rail operation, and additional CMOS inverters can provide a fully digital output. The operation of the comparator provides a logic high while the charge amplifier output exceeds V_{ref}, and a logic low while less than V_{ref}. The comparator output can then be used as a strobe signal to count and monitor detection events.

Since the comparator design is a simple two-stage amplifier, it will suffer from an input-offset voltage. However, in this application, the resolution of small signal inputs is not necessarily required. Instead, to suppress noise induced false detections V_{ref} is often on the order of hundreds of millivolts above the DC level of the charge amplifier.

In order to fully tune the integrated circuitry, all bias voltages were generated off-chip. In addition, feedback capacitor C_f of Fig. 1 was realized through the use of different on-chip poly1/poly2 capacitors. Four capacitors were created with ideal values of 1.5pF, 3.5pF, 10pF, and 20pF. These capacitors can then be connected as C_f through externally controlled switches. Multiple capacitors can be connected in parallel at the same time providing a wide range of values for controlling the conversion gain. The die photo of Fig. 2 shows the selectable bank of capacitors, charge amplifier, and comparators.

B. Hand-held Neutron Detector

With the integrated front-end designed to interface with the B-C diode, a hand-held neutron detector was designed around Atmel's AT91 microcontroller. The microcontroller samples the charge amplifier analog output at 1.3Msamples/sec with 12-bit resolution, and performs real-time processing on the waveform to provide information about each neutron event. A USB interface and custom software modules allow the microcontroller to interface with a computer for capturing, displaying, and storing results. The microcontroller also provides programmable bias voltages for the front-end chip through 12-bit digital to analog converters. A simplified architecture and control flow diagram for the design of the detector is shown in Fig. 3.

The circuit board containing the microcontroller and sensor front-end chip can be seen in Fig. 4. The circuit board was then packaged with an rechargeable battery, LCD display and simple button interface for navigating display menus and

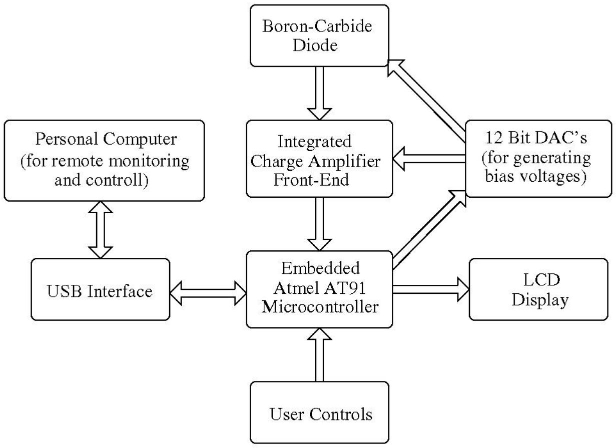

Fig. 3. Architecture and control flow for the design of hand-held neutron detector.

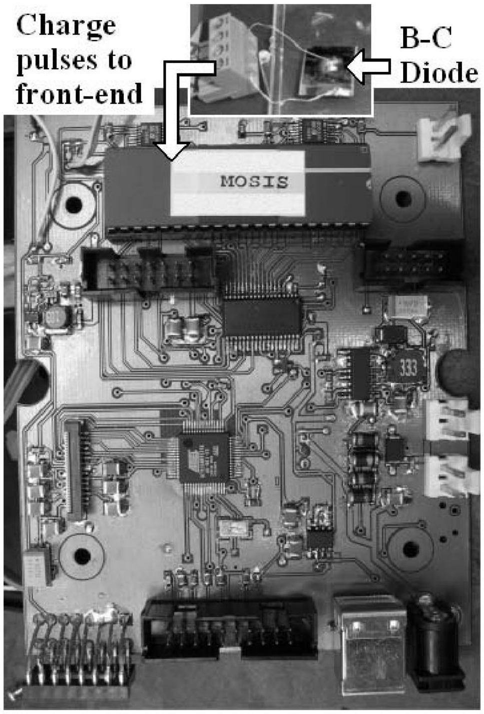

Fig. 4. Custom designed circuit board for hand-held neutron detector containing the front-end microchip and microcontroller. A boron-carbide diode is also pictured.

adjusting the bias voltages of the front-end chip. The overall package of the detector is comparable in size to a hand-held PDA.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The operation of the integrated section was first tested with inputs simulating the charge pulses of the B-C diode. A simple RC differentiator circuit was connected to the charge amplifier input through a coupling capacitor. The negative edges of a square wave input to the differentiator create current pulses flowing in the correct direction. The charge content of the pulses can be controlled by the amplitude of the wave. The resulting output waves for one input falling edge are shown in Fig. 5. The top waveform is the voltage spike created by the charge amplifier. In this case the integrated capacitors were configured to provide a 5pF feedback capacitance. Based on (3), the ideal gain should then be $200\mu V/fC$. The measured gain based on the differentiator circuit and charge amplifier output is approximately $170\mu V/fC$. The slightly lower measured gain is due to the time constant of the charge amplifier feedback which is comparable to the input pulse width. The bottom waveform of Fig. 5 is the comparator output, and shows the digital pulse created while the charge amplifier output exceeds V_{ref}.

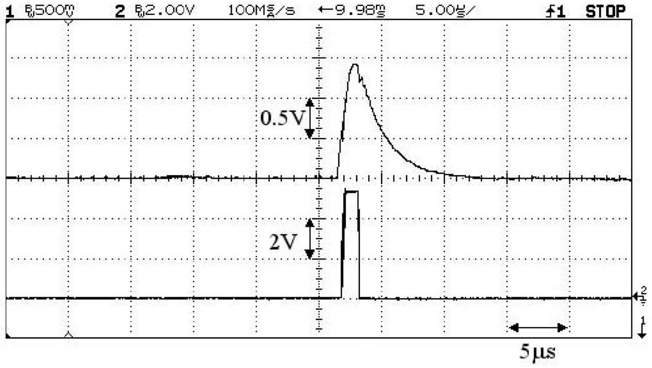

Fig. 5. Oscilloscope captured waveforms of the charge amplifier (top) and comparator (bottom) waveforms created from simulated neutron input.

Neutron testing was conducted with a paraffin moderated plutonium-beryllium neutron source. Calculations of the source estimate a flux rate of approximately 20 neutrons per millisecond over an area of 1cm^2, which is roughly the size of the diode. A typical charge amplifier output waveform captured over a period of 10msec by the sensor system is shown in Fig. 6. The waveform shows several large spikes above a 1V threshold resulting from neutron detection. The number of neutron detections over this period agrees with the flux rate of the neutron source and shows an efficiency of 5% with this threshold setting. In addition, the waveform shows that detected neutrons create voltage spikes noticably larger in magnitude than the system's noise floor. Thus, in this application, the counting and classification operation of the detector is not impacted by the system noise. The slight tailing seen in Fig. 6 is likely due to charge amplifier saturation when neutrons arrive together.

Further confirming the system is detecting actual neutrons can be seen by examining the pulse height spectra measured by the detector. Pulse height spectra is a commonly used measure in particle detection applications. Energy levels are quantized as channels, and detected particles are assigned to a channel based on their energy. The number of events in each channel is then plotted versus the number of channels. The energy of a neutron is proportional to the amplitude of the resulting voltage pulse create by the charge amplifier. The pulse height spectra measured from the neutron source by the detector is

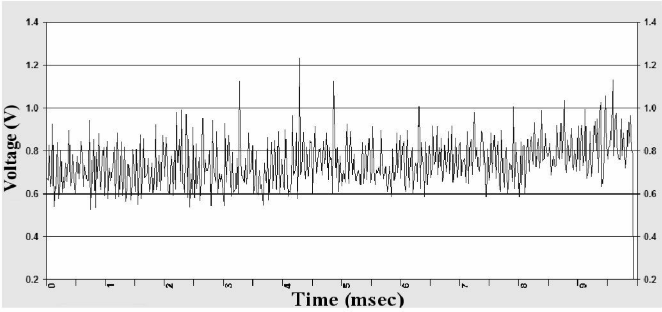

Fig. 6. Charge amplifier output over a period of 10msec showing several large voltage peaks created by incoming neutrons.

shown in the top curve of Fig. 7 a). The predicted spectra based on boron-carbide neutron detection characteristics is plotted in Fig. 7 b). The predicted curve shows a generally decreasing energy spectrum with the exception of two distinct peaks occurring at 2.31MeV and 2.8MeV [9]. These peaks are the sum of the capture product energies of (1). This same general characteristic can also be seen in the measured spectra, with slight variations due to specific B-C diode properties and conversion gain nonidealities.

A final verification of the systems's effectiveness at detecting neutrons can also be seen in the bottom curve of Fig. 7 a). In this experiment a 4mm thick cadmium (Cd) foil was placed over the B-C diode. The Cd foil blocks most incoming neutrons from the diode, and resulted in the substantially lower spectra shown by the bottom result. The small number of neutron detections can be attributed to the imperfect shielding of the Cd foil. When the hand-held unit was removed from the neutron source there were no detected events, indicating that the system does not suffer from false positives.

V. CONCLUSION

This work presented the overall design of a hand-held neutron detector utilizing the new heteroisomeric, all boron-carbide diode. The results presented here conclusively show that the hand-held neutron detector functions as predicted. The B-C diode reacts with incoming neutrons, and the charge amplifier front-end detects the resulting charge pulses and converts them to a voltage signal. The microcontroller architecture then samples that voltage signal at a very high rate. Real-time processing methods on the sampled signal can then successfully classify the energy of incoming neutrons, as seen by the similarity between the actual and theoretical energy spectra.

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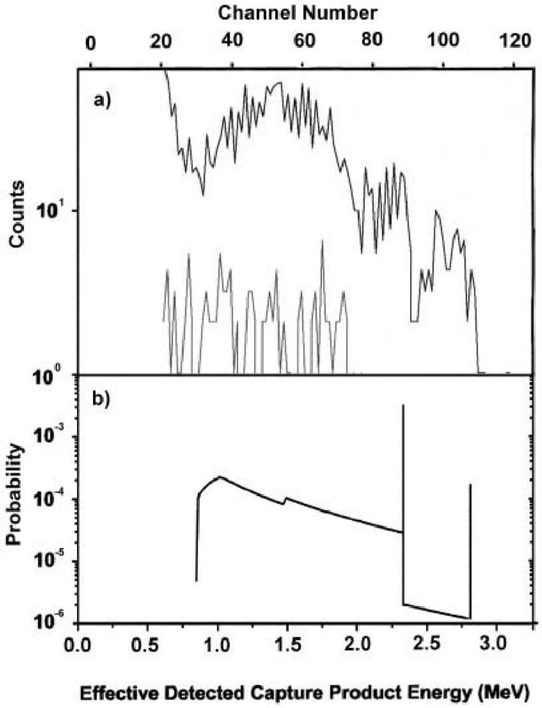

Fig. 7. Measured vs. theoretical neutron pulse height spectra. The top curve in a) is the measured pulse height spectra, and the theoretical pulse height spectra is shown in b). The bottom curve in a) shows the much lower spectra that resulted when neutrons were blocked from the diode.

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